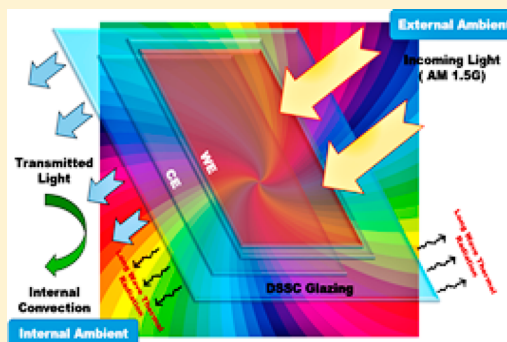


Color Comfort Evaluation of Dye-Sensitized Solar Cell (DSSC) Based Building-Integrated Photovoltaic (BIPV) Glazing after 2 Years of Ambient Exposure

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ABSTRACT: Transmitted external daylight through semitransparent type building integrated photovoltaic (BIPV) windows can alter the visible daylight spectrum and render different colors, which can have an impact on building's occupants' comfort. Color properties are defined by the color rendering index (CRI) and correlated color temperature (CCT). In this work, a less explored color comfort analysis of N719 dye-sensitized TiO₂ based dye-sensitized solar cell (DSSCs) BIPV window was characterized and analyzed after 2 years of ambient exposure. Three different DSSCs were fabricated by varying TiO₂ thickness. The reduced average visible transmission was observed while enhanced color properties were obtained for all three DSSCs. This study could pave way to future developments in the area of BIPV technology using DSSC in terms of their long-term exploration.



1. INTRODUCTION

For a building, lowering energy consumption gets a higher priority, while the most neglected yet often pivotal requirement is visual comfort for dwellers.¹ Visual comfort is attainable by color properties of transmitted daylight through a glazing. Interior visual comfort is achieved when the quality of interior and exterior daylight is equal.² Transparent single and double glazing offers more than 80% transmission, which allows close to equal amount of daylight penetration into an interior. However, high transmission allows a level of penetrated daylight higher than the comfort level, which creates discomfort as well. Thus, color property analysis envisages the indoor visual comfort of a building.³ The color rendering index (CRI) and correlated color temperature (CCT) of transmitted daylight through a glazing is an essential parameter for building interior space comfort.⁴ CRI indicates the accuracy in the colors reproduction through the glazing. On the other hand, CCT resembles the variation of natural daylight, which is measured in Kelvin (K), and it is the temperature of a blackbody radiator with the closest chromaticity to the light source. To evaluate the occupant comfort due to the color property of transmitted solar light, color properties include a suitable CRI > 80 whereas close to 100 is required for higher performance of glazing followed by the CCT variation in between 3500 and 7500 K.⁵

Inclusion of photovoltaic (PV) technology in a building is a holistic approach to harvest benevolent solar energy.^{6,7} Building-integrated photovoltaics (BIPV) replace traditional construction materials, generate benign electricity, and control admitted solar gain and daylight concomitantly.⁸ BIPV as a window application needs semitransparent PV technology.⁹

Dye-sensitized solar cells (DSSCs) based building-integrated photovoltaic (BIPV) windows are promising for low energy building architecture, as fabrication of DSSC involves neither expensive semiconductor substrates nor high-level processing steps, consist of nontoxic and low-cost raw-materials, and spend less energy during the manufacturing process than conventional PV technologies. Therefore, the integrated properties of DSSC-based BIPV implies significant research interest.^{10–13} The transparency of DSSC PV can be altered by tuning the size of titanium dioxide (TiO₂) nanoparticles and the thickness of the film. Moreover, DSSC possesses a positive temperature coefficient compared to crystalline PV cells. A face-to-face electric contact method was developed to fabricate a transparent electric prototype window made with dye-sensitized nanocrystalline TiO₂ solar cells which exhibited 67% of transmittance at 670 nm as shown by Kang et al. (2003).¹⁴ Also, performance evaluation of window units with DSSC having different dyes and thickness, which affect the optical and thermal properties of DSSC, was monitored by Kang et al. (2013).¹² Recently, Lee and Yoon (2018)¹⁵ reported the power performance analysis of a transparent DSSC BIPV window based on 2 year measurement data in a full-scale mock-up. The power yield of the DSSC BIPV windows was analyzed using thermo-monitoring data for 2 years. Values for vertical and sloped DSSC BIPV windows were found to be 2.53 kWh/kW and 3.60 kWh/kW per day, respectively. In addition, Cannavale et al. (2017)¹⁶ showed the potential

Received: June 12, 2019

Revised: August 20, 2019

Published: August 20, 2019

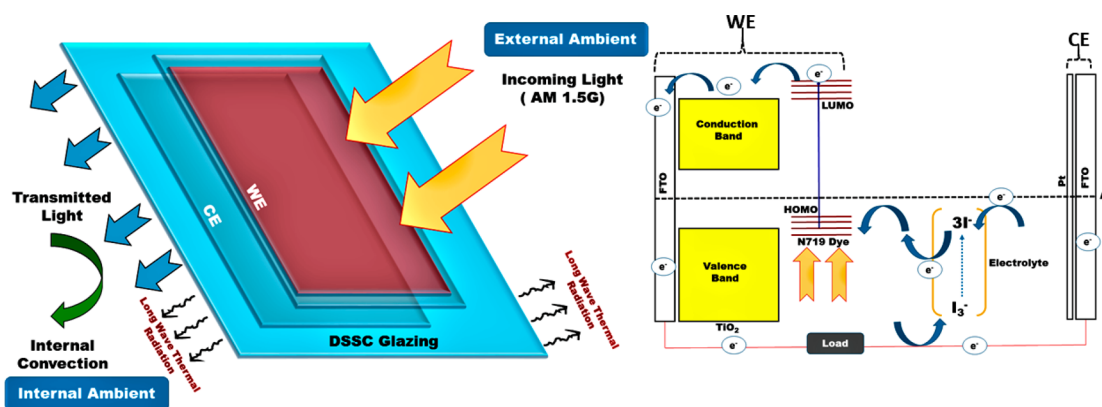


Figure 1. Schematic representation of DSSC glazing and DSSC mechanism.

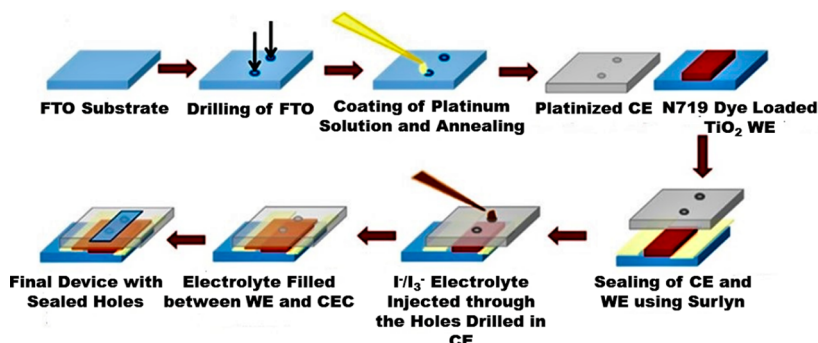


Figure 2. Schematic illustration of the stepwise procedure of DSSC fabrication.

annual energy production followed by visual comfort benefits deriving from the perovskite solar cell based BIPV glazing. A large-area Z-type transparent DSSC module ($300 \times 300 \text{ mm}^2$) connecting the unit cells was applied as a design methodology for BIPV-DSSC glazing.¹³ The advantages of DSSC technology within a PV greenhouse with an optimized choice of photosensitizer over conventional PV due to its distinctive properties toward solar radiation manipulation were discussed in detail. Thermo-opto-electrical characteristics of DSSC were investigated by using Zemax, WINDOW, and COMSOL. DSSC glazing higher than 50% transparent is a potential glazing system for new or retrofit window, as they possess allowable CRI and CCT as reported by Ghosh et. al (2018).¹⁷ Furthermore, the suitability of semitransparent DSSCs for fenestration integration was investigated in terms of clearness index and glazing transmission correlation.¹⁰ In this work, less explored color properties of transmitted solar light such as CRI and CCT were analyzed for DSSC glazing. The transmittance of the DSSCs was measured after 2 years to understand the effects of device stability on DSSC glazing applications. With prolonged time, difficulties in the application of DSSC arise due to the use of liquid-based electrolyte, thereby causes leakage, corrosion and evaporation which retard the electron transfer performance. DSSCs production being nontoxic and cost-effective over conventional PV technologies, making it an environmentally benign product as compared with other PV units.

Variable transmitted light being a dominant parameter for glazing is useful for understanding color comfort of building dwellers. In order to transmit the incident light through a BIPV glazing, semitransparent and transparent DSSCs are required. Previously, color comfort analysis using CCT and CRI for

different other glazing devices was investigated.^{17–26} In this work, long-term stability after 2 years was investigated by studying the color comfort effect of semitransparent DSSC-BIPV glazings at ambient exposure (University of Exeter, Penryn, U.K., 50.16° N and 5.10° W). Figure 1 illustrates the architecture of a DSSC glazing. Fundamental electron transfer pathway of the DSSC device was governed by photochemical cell with two electrodes such as N719 dye sensitized TiO_2 as working electrode (WE) and Pt based counter electrode (CE), an I^-/I_3^- based electrolyte by redox intermediates as shown in Figure 1.

2. EXPERIMENTAL SECTION

Semitransparent DSSCs were prepared according to our previous report.¹⁷ In short, the TiO_2 coated working electrode (WE) and drilled hole containing a Pt coated counter electrode (CE) was assembled into a sandwich-like cell. A hot-melt square gasket of $30 \mu\text{m}$ thick Surlyn thermoplastic sealant was adjusted in such a way that the inner dimensions matched well with the active cell area of the WE. CE was placed on WE, while the Pt-coated conducting side and the dye sensitized metal oxide remained in a face to face configuration. The electrolyte solution was cautiously inserted through the hole of the CE and used to prepare the final sealed DSSC device. Transparent TiO_2 films of different thicknesses such as 3.5 (L2), 6 (L3), and 10 (L5) μm were deposited onto FTO glass using different layers of the TiO_2 paste, respectively. The configuration of a completely fabricated device was schematically presented in Figure 2. The initial devices having an active area of 0.2528 cm^2 exhibited photoelectric conversion efficiencies (PCE) of 2.51, 4.49 and 5.93% under 1 SUN 1.5

AM (WACOM AAA; Model WXS-210S-20; 1000 W/m²; AM 1.5G), respectively.

Color rendering index (CRI) and correlated color temperatures (CCT) are given by the following equations, eqs 1 and 2:^{27,28}

$$\text{CRI} = \frac{1}{8} \sum_{i=1}^8 [100 - 4.6 \sqrt{(U_{t,i}^* - U_{r,i}^*)^2 + (V_{t,i}^* - V_{r,i}^*)^2 + (W_{t,i}^* - W_{r,i}^*)^2}] \quad (1)$$

$$\text{CCT} = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \quad (2)$$

3. RESULTS AND DISCUSSION

Conversion into the CIE 1964 uniform color space system for each test color is performed using color space system $W_{t,i}^*$, $U_{t,i}^*$, $V_{t,i}^*$ whereas $W_{r,i}^*$, $U_{r,i}^*$, $V_{r,i}^*$ represents each test color, lighted by the standard illuminant D65 without the glazing, where $n = \frac{(x - 0.3320)}{(0.1858 - y)}$ and x, y chromacity coordinates are used. The details of these parameters can be found elsewhere.^{4,17,19}

Figure 3 indicates the visual transmittance change of DSSC glazing after 2 years at ambient exposure. The average visible

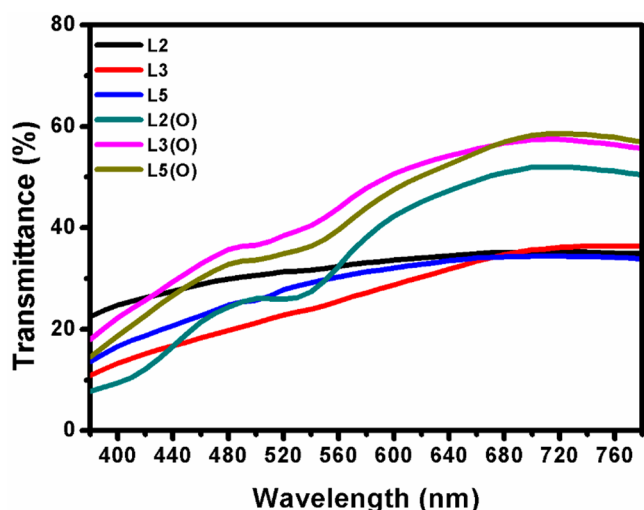


Figure 3. Change of visible transmittance of DSSC glazing where O stands for initial (old).

transmittance (AVT) changed from 35 to 31%, 44 to 26%, and 42 to 28% for L2, L3, and L5 devices, respectively. A clear material degradation was observed in the range between 380 and 520 nm. Mostly, DSSCs are vulnerable to continuous irradiation of ultraviolet (UV) light for outdoor stability. TiO₂ nanoparticles coated photoanode absorb UV light, they act as a photocatalyst inducing the degradation of the sensitizing dye. Also, the I⁻/I₃⁻ liquid electrolyte are reduced irreversibly on the TiO₂ surface to colorless iodide ions by the photocatalyst effect, followed by inducing a lack of reversible redox reaction of the electrolyte. The degradation also causes agglomeration of the dye and TiO₂ molecules that rather remains in sensitized condition resulting in lesser transparency. DSSCs without UV cutoff filter show higher photoconversion efficiencies but lower stability at outdoor conditions. On the contrary, DSSCs with UV cutoff filter have higher stability at outdoor conditions but lower PCE due to a large amount of incident light loss.²⁹ In

this regard, Han et al. (2015) reported 18% higher relative photoconversion efficiency after 48 days of outdoor conditions compared to a DSSC using a commercial UV cutoff filter using 1,8-naphthalimide derivatives.³⁰

Figure 4 illustrates the CCT and CRI for DSSC glazing before and after 2 years at ambient exposure. Improved CCT

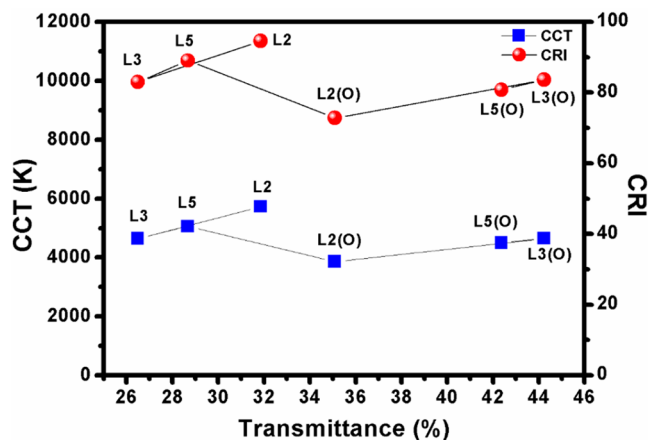


Figure 4. Variation of CCT and CRI with visible transmittance where O stands for initial (old).

and CRI were observed after 2 years compared to an older one. It is interesting to monitor that average visible transmission was reduced after 2 years whereas enhancement happened for color properties. This predicts that CCT and CRI are not single transmittance dependent values but give spectral dependent parameters, and these include D65 and spectral power distribution of natural daylight. For all three types of devices, transmission became lower after 520 nm. Maximum enhancement of CRI occurred for the L2 device which was from 72 to 94 while L3 changed from 83 to 82 and L5 changed from 80 to 89 (Table 1). Reduction of AVT, in turn, reduces

Table 1. Details of Spectral and Color Properties of Three Different TiO₂ Thickness DSSCs

device	L2	L3	L5
thickness (μm)	3.5	6	10
AVT (old)	35%	44%	42%
AVT (after 2 years/present)	31%	26%	28%
CCT (K) (old)	3860.5	4647	4501.7
CCT (K) (after 2 years/present)	5729.5	4637.9	5056.9
CRI (old)	72	83	80
CRI (after 2 years/present)	94	82	89

the entering solar heat gain into indoor space. Moreover, it is clear in this part that reduced AVT of this particular type of devices enhances the color comfort. Hence this device is suitable for semitransparent BIPV window integration for warm and summer seasons. Compromised power reduction is an issue with this type of device, although when building energy is evaluated, only power generation from the windows gets less priority. Table 1 illustrates the details of different parameters for investigated DSSCs.

4. CONCLUSIONS

In this work, ambient exposed DSSC glazing was investigated for color comfort analysis 2 years after its fabrication. Three different semitransparent DSSC samples were fabricated by

varying the TiO₂ thickness. CCT and CRI, which are the two key parameters used to understand color comfort, were calculated from the measured visible transmittance. While 30.5% CRI enhancement occurred for the L2 device, visible transmittance changed by only 11.4%. This result established that reduced AVT and enhanced color properties make this DSSC a potential candidate for low energy building integration for a warmer season and hot climate.

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ACKNOWLEDGMENTS

This work was supported by a EPSRC IAA grant received by A.G. This work has been conducted as part of the research project “Joint UK-India Clean Energy Centre (JUICE)”, which is funded by the RCUK’s Energy Programme (Contract No.: EP/P003605/1). The project’s funder was not directly involved in the writing of this article. In support of open access research, all underlying article materials (data, models) can be accessed upon request via email to the corresponding author.

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