COMFORT AT THE EXTREMES

INVESTING IN WELL-BEING IN A CHALLENGING FUTURE

Jessica Fernández-Agüera
Samuel Domínguez-Amarillo
Susan Roaf

Colourful Daylight: Evaluating the spectral transmittance of daylight through window films

[1]*Mino-Rodriguez, I., [2]Balakrisnhan, P., [2,3]Karmann, C., & [2]Sepúlveda, A.

*lead presenter
[1] isabel.mino@kit.edu, Building Science and Technology (BST), IEB, Karlsruhe Institute of Technology, Germany
[2]Laboratory of Architecture and Intelligent Living (AIL), IEB, Karlsruhe Institute of Technology, Germany
[3]Institut TRANSFORM, Haute École d'Ingénierie et d'Architecture de Fribourg (HEIA-FR), Fribourg, Switzerland

Abstract

In recent years, window films have emerged as a popular solution for managing solar heat gains across diverse climatic conditions, ranging from extreme to moderate weather. While these films effectively reduce unwanted heat gains, they often compromise daylight availability and modify the colour of natural light. This study quantifies the spectral irradiance of window films, serving as a basis for energy, daylight, and colour assessment. We looked at high and low transmittance levels for correspondingly moderate and extreme weather conditions.

A comprehensive analysis was conducted on 14 different window films, with visual transmittance from approximately 6% to 86%. The spectral power distribution (SPD) of each film was meticulously measured using a spectrometer. The collected data provide a holistic visual and non-visual evaluation of the films' performance.

The results reveal significant insights into the trade-offs between visual transmittance and correlated colour temperature (CCT). High transmittance films allow more natural light penetration but can lead to unwanted heat gains. Low transmittance films effectively block solar heat but often at the cost of reduced daylight and altered colour rendering. The study discusses the advantages and disadvantages of the evaluated films.

Finally, this research highlights the need for a balanced approach when choosing window films, considering daylight quality. The findings serve as a valuable resource for architects, building engineers, and environmental designers seeking to optimise building performance with visual and non-visual aspects of daylight through informed decisions on spectral evaluation of windows films.

Keywords

Daylight, spectral transmittance, windows films.

Introduction

Building façade elements have gained significant attention due to their essential role in ensuring a comfortable indoor environment and reducing energy consumption in buildings. Among these, fenestration elements—such as windows—are considered the weakest thermal components of the building envelope due to their low thermal resistance and high transmittance of solar gains. Traditionally, transparent façade elements are evaluated using metrics such as thermal transmittance (U-value) and solar heat gain coefficient (SHGC) related to building energy efficiency. However, daylight plays a vital role in human health and well-being beyond energy considerations. Since the discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) and their impact on circadian rhythms (Berson et al., 2002; Brainard et al., 2001), the effects of light on human physiology and psychology have attracted growing interest (Englezou & Michael, 2023; Fernandes et al., 2017). The physiological impact of daylight on humans depends on light exposure's intensity, colour, duration, and timing. Static or constant spectral power distributions can disrupt the circadian rhythm, leading to issues such as "Circadian-Time Sickness" and "Social Jetlag" (Fernandes et al., 2017).

With modern advancements, a wide variety of glazing systems are available, providing opportunities to enhance energy efficiency in new construction projects. However, when retrofitting existing buildings, the application of window films offers a cost-effective solution. Window films have become popular for improving energy efficiency and thermal comfort across diverse climatic conditions, ranging from extreme to moderate weather (Ghaeili et al., 2023; Hui & Kwok, 2006). These films reduce solar radiation, ultraviolet (UV), and infrared (IR) transmission, lowering unwanted solar heat gain. However, while they reduce solar heat gains, they can also affect daylight transmission, impacting occupants' visual comfort and overall well-being. It is worth noting that excessive filtering of specific wavelengths by window films can impact the perceived quality of light, affecting mood, productivity, and circadian rhythms. Besides, maintaining adequate daylight levels has been linked to better health outcomes, such as improved sleep quality, enhanced mental well-being, and higher productivity, particularly in workplaces.

Several studies have examined the performance of window films in terms of energy savings (Hui & Kwok, 2006; Li et al., 2015). Hui's work focused on the thermal, solar, and visual performance of window films, finding that films effectively limit the transfer of infrared solar heat. Li's research compared glass surface temperatures with and without films, noting that films performed better on clear glass than tinted or laminated glass, with significant energy-saving potential in commercial and office buildings.

Moreover, some researchers have focused on understanding the effects of light colour on comfort, among others. Chinazzo et al. (2021) studied the effects of coloured glazing (blue, orange and neutral). Results indicated that users mostly preferred neutral glazing over the two saturated ones. In comparison, orange glazing was associated with relaxing and warmest daylight. The main metric for assessing the colour of light is the correlated colour temperature (CCT). However, reducing the complex spectral power distribution and chromaticity coordinates to a single CCT value can result in the loss of critical information. To address this issue, the Duv (distance from the Planckian locus in the uniform chromaticity scale) metric has been suggested as a means to measure the light divergence from the Planckian locus, overcoming some of the limitations associated with using CCT alone (Durmus, 2022).

Recent studies have also shifted towards understanding how window films impact circadian lighting. Using simulation tools, Ghaeili et al. (2023) assessed various glazing systems for their circadian light performance. They found that well-designed window systems could provide adequate circadian lighting by transmitting the right quantities and wavelengths of solar and sky radiation. However, challenges remain in balancing both photopic light provision and circadian light requirements. Similarly, Englezou and Michael (2023) explored the impact of natural lighting spectrum variability, assessing light intensity, spectrum, and its variation across seasons and times of the day. Their study confirmed that seasonal and hourly variations significantly affect melanopic equivalent daylight illuminance (melanopic-EDI) levels, with winter conditions providing the highest melanopic-EDI values due to lower sun angles and direct sunlight exposure. Moreover, Khaled and Berardi (2023) experimentally characterised five commercial photochromic window films, revealing their ability to enhance energy savings and improve indoor daylight conditions. Retrofitting office buildings with these films not only improved visual comfort but also contributed to enhanced energy efficiency.

This paper aims to comprehensively evaluate the performance of window films regarding daylight quality and quantity using visual and non-visual metrics. Visual metrics include visual transmittance (Tvis) to address the amount of natural daylight entering a space and the CCT and Duv. On the non-visual side, melanopic-EDI is used to assess light's impact on circadian rhythms. This study quantifies the spectral irradiance of 19 commercially available window films, serving as a basis for daylight, colour and melanopic-EDI assessment. The motivation for this study stems from the need for a holistic evaluation of window film performance, incorporating visual and non-visual responses.

Methodology

This section outlines the approach taken to evaluate the spectral performance of various window films. This study involved selecting a representative sample of films, conducting precise spectral measurements under clear sky conditions, and a systematic data analysis. The aim is to provide a detailed and accurate assessment of the film's performance in relation to key metrics.

Sample selection

In this paper, we are investigating neutral window film with both low and high visual transmission (Tvis). Thus, the sample selection used a convenience sampling method to choose the window film samples. The initial sampling screening included 57 films from various manufacturers that promoted neutral colour films. After direct communication with the manufacturers or distributors, we obtained and included in the analysis 19 film samples. Table 1 summarises the visual light transmission (Tvis) and the reduction in these films' solar glare (glare reduction), as reported by the manufacturers.

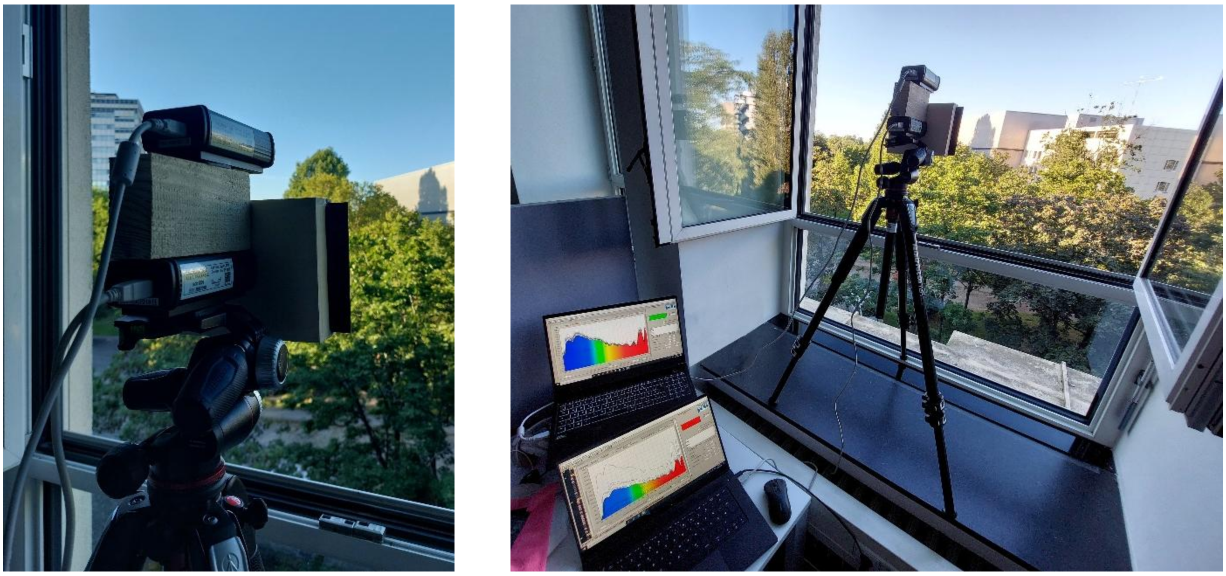
Table 42: Summary of windows film properties as reported by the manufacturers, light transmission and glare reduction

Id	Code	Description	Tvis (%)	Glare Reduction (%)
1	05xrs	05 xrs extreme dark	6	89
2	sv10	Scenic View - SV 10	8	91
3	15xrs	15 xsr dark	14	78
4	80xc	Natural 80 XC	20	81
5	pg20	Prestige 20	21	77
6	275xc	Titane 275 XC	22	80
7	pd45	Palisade - PD 45	44	47
8	pg40	Prestige 40	42	53
9	pd40	Palisade - PD 40	38	56
10	sv50	Scenic View - SV 50	50	44
11	dn60	Daylight natural - DN 60	63	30
12	sun70	Sunlight - SUN70	67	25
13	80sr	Heat uv 80sr	70	21
14	30c	Spectra 30 C	70	30
15	333xc	Clarity 333 XC	73	29
16	80ex	Heat uv 80ex	78	26
17	22xc	Spectra 22 XC	78	18
18	15c	Spectra 15 C	86	13
19	pg70	Prestige 70	71	20

Spectral measurement

Spectral measurements were conducted using two Jeti spectroradiometers (Specbos 1201M) with a wavelength range of 380 to 780 nm, capturing data at 1 nm intervals. Two measurement setups were performed, and in each setup, the devices were used simultaneously to measure spectral irradiance. The first measurement setup – used for the cross-calibration process – involved placing the two spectroradiometers side by side to capture the spectral power distribution (SPD) of a clear sky for their cross-calibration. In measurement setup 2, the two spectroradiometers were vertically aligned, as shown in Figure 1 (a), with one having a film and the other without, to conduct repeated measurements of all the selected films. The distance between the two spectroradiometers was kept to a minimum of (mention distance here), ensuring both devices captured the spectral irradiance of a similar scene under stable, clear sky conditions, without the sun or clouds in the scene (Figure 1(b)). A total of 19 pairs of spectral irradiance data were collected in this setup.

All the measurements were conducted from a north-east oriented window on a single summer day (August 8th, 2024) between 19:15 and 19:40, within a 25-minute window. During this time window, the change in solar altitude angle was four degrees. The spectral power distribution of spectral irradiance [W/(sqm*nm)] was measured at a 1nm resolution. Additionally, the following parameters were also recorded: Ev [lx] (CIE1931 2°), CCT [K] (CIE1931 2°), and x, y coordinates.



(a) (b)

Figure 80: Spectral measurement setting, a) spectrometer position and b) overall setup.

Data analysis

Data cleaning utilised R version 4.3.3 (RStudio team, 2020) for data cleaning, processing and subsequent analysis. This process involved a series of steps, including cross-calibration, normalisation and calculation of variables.

In order to remove the instrumental influence of the measurement and ensure the spectral data is comparable, cross-calibration between the two spectroradiometers was performed to obtain a correction factor. The correction factor was calculated using Equation 1, and the simultaneous spectral irradiance measurements were conducted during the first measurement setup. Measurements from Jeti1 served as the reference values (x_{ref}), while measurements from Jeti2 (x_{mea}) were corrected using the calculated correction factor (*cf*) described in Equation 1. The correction factor was applied to SPD, Ev, CCT and x,y coordinates, the corrected values are referred to as x_{mea*}

$$cf = x_{ref} / x_{mea} \tag{3}$$

Lastly, all spectral irradiance data was normalised at 560nm (Equation 2) to allow for a relative comparison of the spectral irradiance data measured. SPD norm (λ) is the spectral irradiance at wavelength λ, and SPD (560) is the spectral irradiance at wavelength 560nm.

$$SPD_{norm}(\lambda) = SPD(\lambda)/SPD(560) \tag{2}$$

Performance evaluation

The study evaluated the daylight performance of the films using both visual and non-visual metrics, as described below, along with error metrics to quantify the difference between spectral daylight measured without the film (referred to as 'sky') and spectral daylight measured through the films (referred to as 'film'). Visual metrics include correlated colour temperature (CCT), visual transmittance (Tvis), Duv, and photopic illuminance, while non-visual metrics focus on melanopic-EDI to assess the circadian impact.

Error metrics, such as Mean Absolute Error (MAE) and Mean Relative Squared Error (MRSE), were applied to measure the spectral differences between the normalised spectral values of the 'sky' and those of the 'film', providing a clear indication of the quality and quantity of daylight transmitted through the films. As the measurements were not taken under controlled conditions, the analysis focused on the relative differences between the film and sky spectral data.

- **Relative CCT Deviation:** The calculation of the relative CCT deviation involved the difference between the corrected CCT* with films and the CCT of the sky, as described in Equation 3.

  $$cct_{rel} = (cct_{film} - cct_{sky}) / cct_{sky} \quad (3)$$

- **Visual Transmittance:** The visual transmittance was computed as the ratio of the illuminance measured with films (illum_film) to the illuminance measured without films (illum_sky).
- **Duv** and **Relative Duv:** The calculation of Duv followed the method described by (Ohno et al., 1991), with relative Duv defined as the absolute difference between Duv_sky and Duv_films*. American National Standards Institute (ANSI, 2016) and EnergyStart Certification (ENERGY STAR®, 2011) recommend Duv values between ±0.006 and Duv between ±0.003 when more demanding colour quality of light is preferred (Durmus, 2022).
- **Melanopic-EDI:** The melanopic-EDI is calculated per the International Commission on Illumination (CIE) Standard S 026/2018 (Balakrishnan et al., 2023; CIE, 2018).
- **Photopic illuminance:** The photopic illuminance is calculated as per the CIE018:2019.
- **M/P:** The ratio between the melanopic-EDI and Photopic illuminance.
- **MAE** and **RMSE**: The mean absolute error (MAE) and root mean square error (RMSE) were calculated from the normalised spectral data.

Results and discussion:

The daylight spectral irradiance measured through the 19 window films (SPD Film), compared to their respective daylight spectral irradiance measured without the films (SPD Sky), is shown in Figure 2. To enhance the visual clarity of the remaining curves, those with excessively high errors—specifically IDs 1 and 3—were omitted, as their high error values flattened the other curves.

Assessing the quality of daylight filtered through each film requires evaluating the similarity between the SPD curves of the films and the SPD of the sky. The SPD of films 6, 11, and 14 closely matches the SPD of the sky, whereas films 2 and 5 diverge significantly. A close match to the sky SPD curve indicates good transmission of various daylight wavelengths, whereas diverging curves suggest poor spectral transmission.

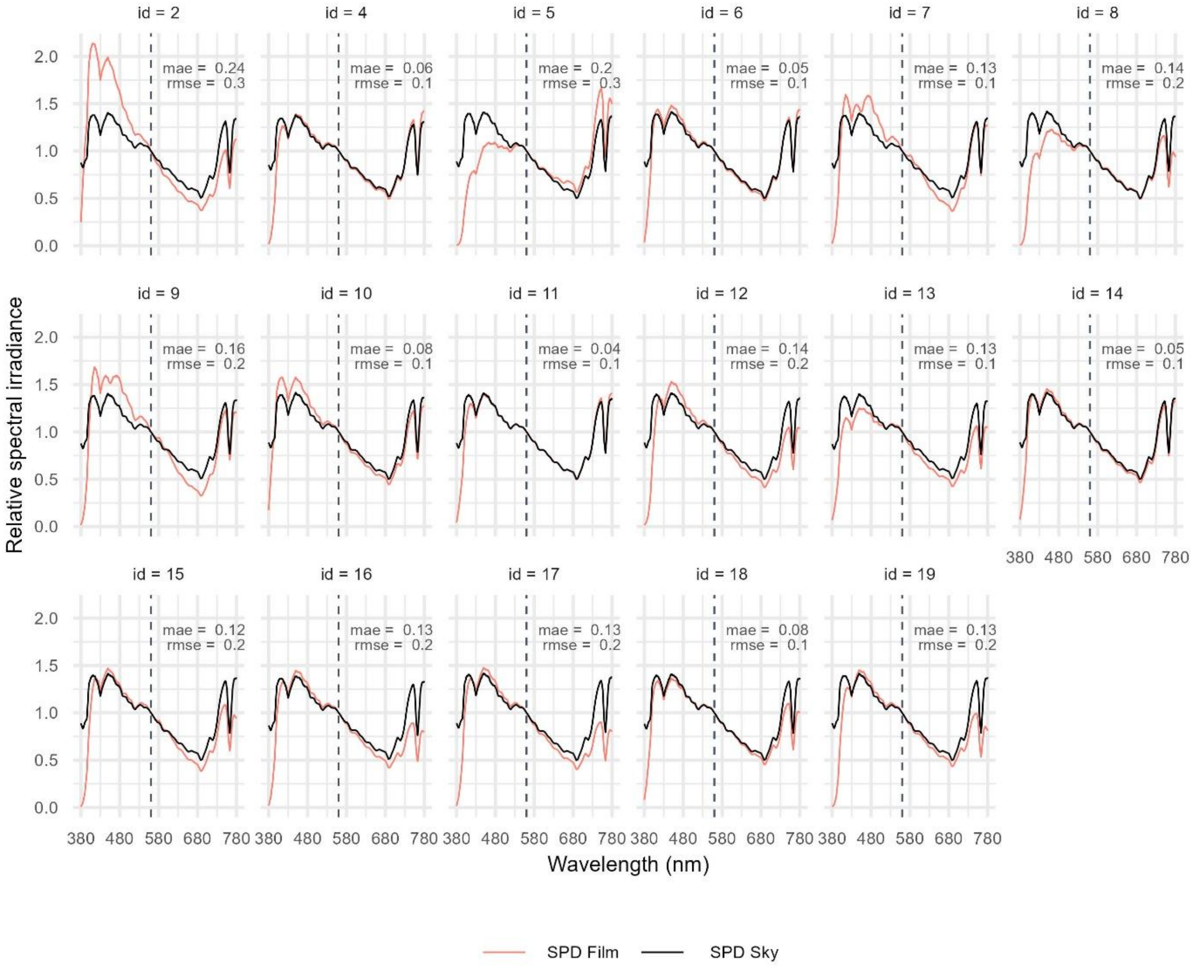


Figure 81: Normalised Spectral power distribution of the sky (SPD sky) and films (SPD with film), and the mean absolute (mae) and root mean square (rmse) errors.

To quantify how closely an SPD film curve follows the corresponding SPD sky curve, the MAE and RMSE were calculated. The combined MAE and RMSE errors are plotted in Figure 82. To categorise the errors relatively, we grouped the results into three categories: low, medium, and high.

Low errors (error ≤ 0.2) are observed for films ID 6, 10, 11, and 14. Most of the assessed films fall into the "medium" error category (0.2 < error ≤ 0.4), including films ID 4, 7, 8, 9, 12, 13, 15, 16, 17, 18, and 19. Finally, "high" errors (error > 0.4) were observed for films ID 2 and 5. Unsurprisingly, the highest errors were observed in films with the lowest visual transmittance.

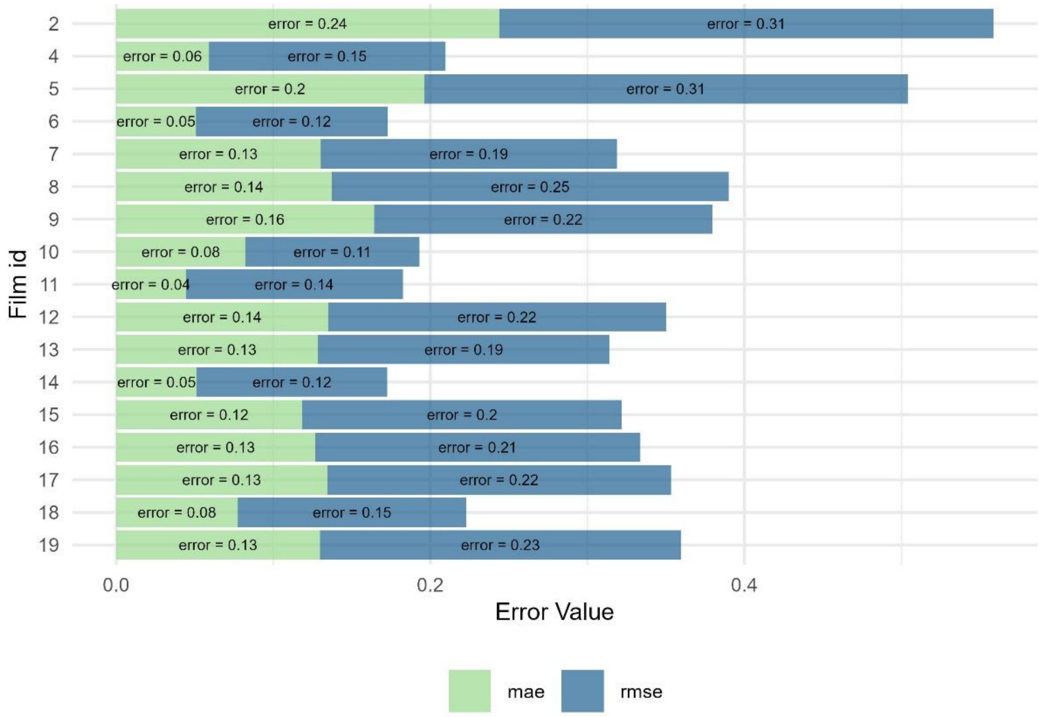


Figure 82: Comparison of the mean absolute (mae) and root mean square (rmse) errors.

Further analysis of the films' colour rendition is presented in Figure 4, which illustrates the relative differences between the correlated colour temperature (cct_rel) of the film and the sky, as well as the relative differences in Duv (duv_rel) between the film and the sky. These metrics quantify the extent to which the window films change the colour of daylight passing through them.

Films with minimal deviations in both CCT and Duv preserve better colour neutrality, maintaining the natural appearance of daylight. In contrast, several films, such as IDs 2, 5, 9, and 13, exhibit significant deviations in both metrics, indicating a pronounced shift from the natural daylight of the sky. On the other hand, films such as IDs 6 and 11 show minimal deviations in both CCT and Duv, demonstrating superior colour rendition and a closer match to the sky's daylight characteristics.

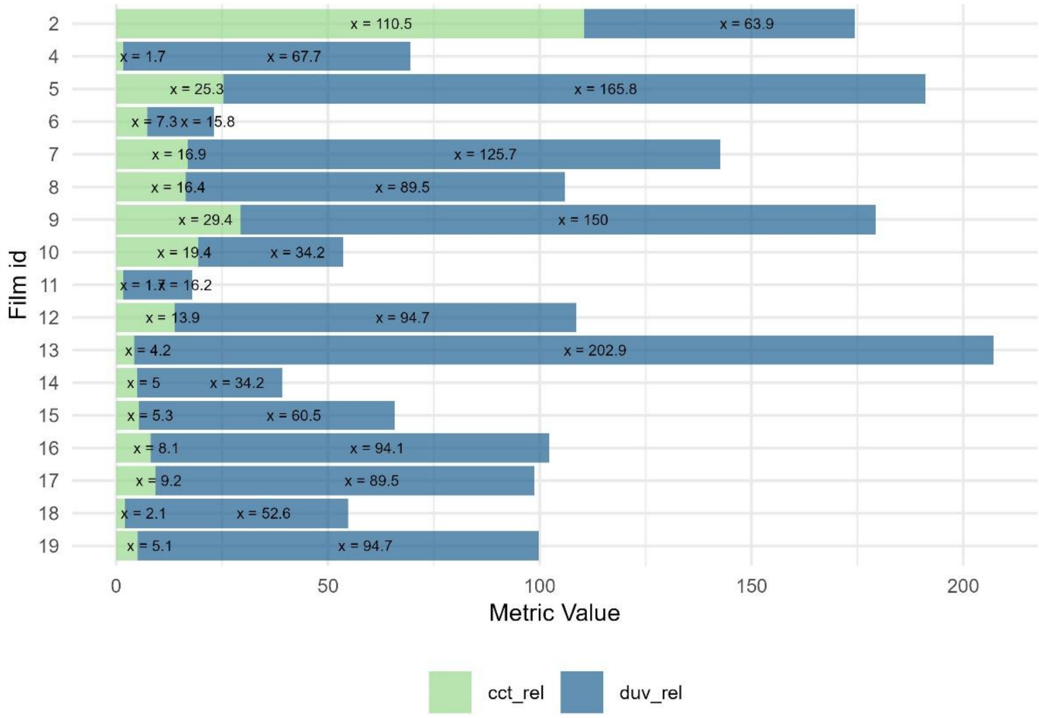


Figure 83: Comparison by window film of the Relative CCT deviation (cct_rel) and the relative Duv deviation (duv_rel)

Lastly, Figure 84 summarises the relationship between photopic illuminance, melanopic-EDI, and the melanopic-EDI/photopic illuminance ratio (M/P). In the figure, grey dots represent cases where the M/P ratio lies between 0.95 and 1.05 (close to neutral), while blue dots indicate instances where the M/P ratio exceeds 1.05.

Considering that lower IDs correspond to lower visual transmittance and higher IDs correspond to higher visual transmittance, a higher visual transmittance is associated with higher melanopic-EDI values and, consequently, higher photopic illuminances. When examining the M/P relationship, most films show a greater effect on melanopic-EDI (M/P values above 1.05). This is expected because the SPD of the sky—at the time of data collection—peaks in the blue-cyan spectral range, which coincides with the peak sensitivity of the melanopic-EDI curve. However, films 5 and 8, which have M/P ratios between 0.95 and 1.05, demonstrate that these films block the visible light spectrum in the blue-cyan range, as observed in Figure 1.

It is important to note that these observations regarding non-visual effects are not conclusive, as the data were collected at a single point in time and do not account for daylight variability throughout the day or across seasons.

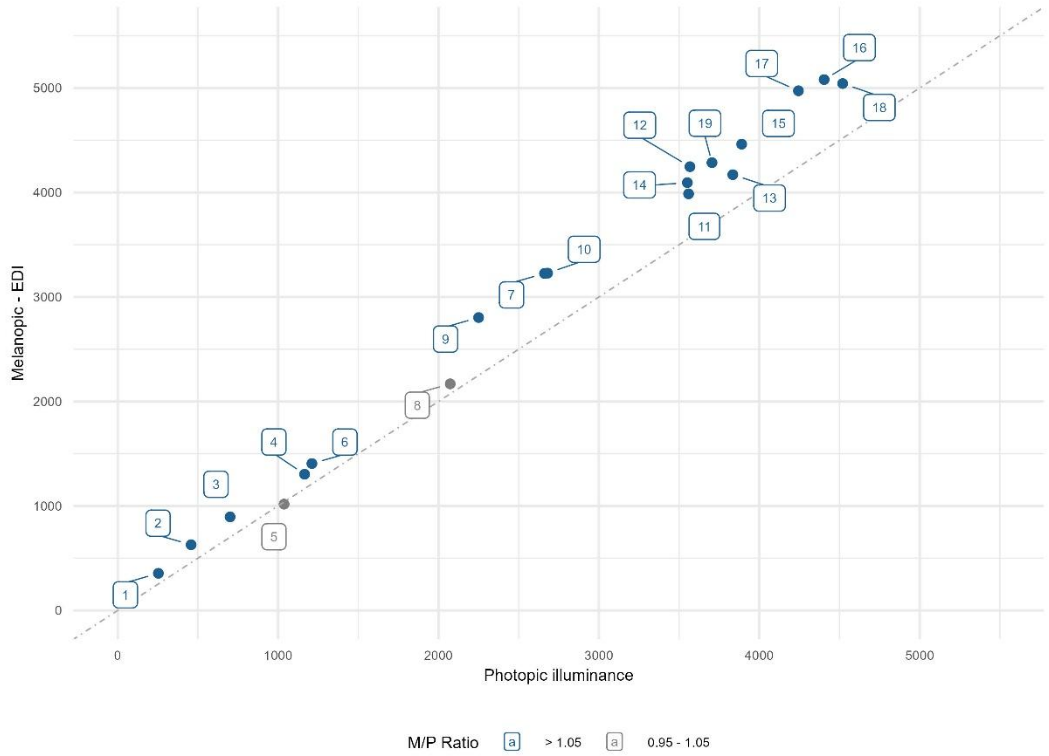


Figure 84: Relation of the Photopic illuminance and melanopic-EDI and the M/P ratio

The performance of a window film would provide different results depending on the combination of variables considered. No film can be deemed the best across all visual, non-visual, and error metrics. A combined score that includes (weight) for the relative Duv, relative CCT, melanopic-EDI, and errors could allow for a comprehensive evaluation where the weights are defined according to the specific needs of each case study. The choice of window film will ultimately depend on the priority given to each performance criterion, such as colour accuracy, daylight transmission, or non-visual effects like melanopic response. Therefore, selecting the optimal film is context-dependent, and a flexible approach to weighting these variables is essential for making informed decisions.

Conclusions

This study comprehensively evaluated the performance of 19 commercially available window films using both visual and non-visual metrics, focusing on the quality and quantity of daylight transmitted. We assessed how closely each film matched the sky's daylight spectrum by analysing spectral power distributions (SPD) normalised at 560 nm. Films such as IDs 6, 10, 11, and 14 exhibited good spectral fidelity, closely transmitting the daylight characteristics of the sky. In contrast, films like IDs 2 and 5 showed significant deviations, indicating a less accurate match to the natural SPD of daylight. Lower visual transmittance films, such as IDs 1 and 3, demonstrated higher errors, as expected, due to their design to block a significant portion of the visible light spectrum. Films with visual transmittance above 20% displayed medium errors, reflecting a balance between light transmission and spectral accuracy.

The colorimetric evaluation, based on the relative differences in CCT and Duv, further highlighted the superior performance of films such as IDs 6 and 11, which closely preserved the daylight's colorimetric characteristics. Conversely, films like IDs 2, 5, 9, and 13 exhibited greater deviations, indicating pronounced alterations in the transmitted light's colour rendition. Such modifications impact not only the visual intensity and colour but also the physiological responses of occupants, with potential implications for health, well-being, and productivity.

The study concludes that no single window film excels universally across all visual and non-visual metrics. The optimal film choice depends on the relative importance of factors such as colour accuracy, spectral daylight transmission, melanopic-EDI, and error metrics like MAE. While a composite performance score could be calculated to integrate these metrics, such an approach would require carefully weighted factors reflecting the specific priorities of the intended application. Consequently, selecting the most appropriate window film is highly context-dependent, requiring a flexible balance between competing performance metrics.

Future research could expand on this study by evaluating the performance of window films under varying daylight conditions throughout different times of the day and across seasons, capturing the dynamic nature of natural light. Additionally, incorporating energy-saving potentials into the analysis would provide a more holistic understanding of the film's impact, addressing their optical properties and contribution to building energy efficiency.

Acknowledgements

Isabel Mino-Rodriguez is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under the project number 498385769.

References

ANSI. (2016). *American National Standard for Electric Lamps—LED (Light Emitting Diode) Lamps—Method of Designation*.

Balakrishnan, P., Knoop, M., & Doppler, L. (2023). A framework to generate local spectral skies for spectral daylight simulations. *Journal of Physics: Conference Series*, *2600*(11). https://doi.org/10.1088/1742-6596/2600/11/112001

Berson, D. M., Dunn, F. A., & Takao, M. (2002). Phototransduction by retinal ganglion cells that set the circadian clock. *Science*, *295*(5557), 1070–1073. https://doi.org/10.1126/science.1067262

Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action Spectrum for Melatonin Regulation in Humans Evidence for.pdf. *The Journal of Neuroscience*, *21*(16), 6405–6412.

Chinazzo, G., Wienold, J., & Andersen, M. (2021). Effect of Indoor Temperature and Glazing with Saturated Color on Visual Perception of Daylight. *LEUKOS - Journal of Illuminating Engineering Society of North America*, *17*(2), 183–204. https://doi.org/10.1080/15502724.2020.1726182

CIE. (2018). *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*. CIE Central Bureau. https://doi.org/10.25039/S026.2018

Durmus, D. (2022). Correlated colour temperature: Use and limitations. *Lighting Research and Technology*, *54*(4), 363–375. https://doi.org/10.1177/14771535211034330

ENERGY STAR®. (2011). *Program Requirements for Integral LED Lamps, Eligibility Criteria - Version 1.4*. 35. https://www.energystar.gov/sites/default/files/specs//Version 6 1 Computers Final Program Requirements.pdf

Englezou, M., & Michael, A. (2023). Investigation of the daylight spectrum in an indoor environment using CIE S 026 melanopic metrics. *Lighting Research and Technology*, *55*(7–8), 690–711. https://doi.org/10.1177/14771535231204162

Fernandes, G. E., Bohar, J., & Xu, J. (2017). Spectral-Temporal LED Lighting Modules for Reproducing Daily and Seasonal Solar Circadian Rhythmicities. *2017 IEEE International Conference on Smart Computing, SMARTCOMP 2017*, *May*. https://doi.org/10.1109/SMARTCOMP.2017.7947047

Ghaeili, N., Beiglary, S., Wang, J., & Jao, Y.-L. (2023). *Assessment of the Window Performance from the Light Provision and Circadian Light Aspects* (Issue August). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-39147-7_6

Hui, S. C. M., & Kwok, M. K. (2006). Study of thin films to enhance window performance in buildings. *Proceedings of the Sichuan-Hong Kong Joint Symposium 2006*, *July*, 158–167.

Khaled, K., & Berardi, U. (2023). A cross-climate assessment of the visual and energy performance of flexible photochromic films for in-situ window retrofits. *Energy and Buildings*, *300*(October), 113664. https://doi.org/10.1016/j.enbuild.2023.113664

Li, C., Tan, J., Chow, T. T., & Qiu, Z. (2015). Experimental and theoretical study on the effect of window films on building energy consumption. *Energy and Buildings*, *102*, 129–138. https://doi.org/10.1016/j.enbuild.2015.04.025

Ohno, H., Kuno, S., Saito, T., Kida, M., & Nakahara, N. (1991). The effects of hypobaric conditions on man's thermal responses. *Energy and Buildings*, *16*(1–2), 755–763.

https://doi.org/10.1016/0378-7788(91)90048-8
RStudio team. (2020). RStudio: Integrated Development for R. In *RStudio, Inc., Boston, MA* (p. http://www.rstudio.com/.-http:&#x2F). PBC. http://www.rstudio.com/