Comprehensive evaluation of windows integrated semi-transparent PV for building daylight performance

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Abstract

Building-Integrated Semi-transparent Photovoltaics Window (PV window) has been considered as one of the potential candidates to replace conventional windows to improve buildings' energy efficiency hence reducing their carbon emission. With the integration of PV windows, the indoor luminous-environment may be significantly affected. The presence of solar cells may cause undesirable shading, low illuminance level and affect colour quality of the transmitted daylight. Therefore, it is important to comprehensively assess daylight performance of PV windows to ensure a comfort luminous environment. In this study, the daylight performance of CdTe PV window with four different transparencies (i.e. 20%, 30%, 40% and 50%) applied to a typical office have been assessed in terms of daylight quantity and daylight quality. RADIANCE was selected to predict the annual daylight performance through advanced dynamic metrics including Useful Daylight Illuminance (UDI), Daylight Glare Probability (DGPs) and Illuminance Uniformity (Uo). Correlated Colour Temperature (CCT) and Colour Rendering Index (CRI), which are two attributes to characterise colour quality of transmitted daylight specified in CIE standard, were used to evaluate performance of the selected PV windows. CCT and CRI were calculated under three CIE standard daylight scenarios (CCT of 4000 K, 6500K and 25000K respectively). It is found that CdTe PV window can significantly improve the homogeneity of daylight distribution on the task area and reduce risks of daylight glare when compared to these of a conventional double glazing. Moreover, recommended CCT (i.e. 3300-5000K) can be achieved with the employment of CdTe PV window under the 4000 K and 6500 K daylight scenarios. All types of CdTe PV windows can maintain a CRI at a comfortable level i.e. above 90 under the three tested daylight scenarios.

Keywords: CdTe PV window; daylight quantity; daylight quality; RADIANCE; CCT; CRI

Nomenclature	
τ_v	Visible light transmittance
$\tau_v(\lambda)$	Spectral transmittance
$SPD(\lambda)$	Relative spectral power distribution
$V(\lambda)$	Spectral luminous efficiency for photopic vision defining the standard observer for photometry
$\bar{x}\bar{y}\ \bar{z}$	CIE standard colour-matching functions for the CIE 1931 2º Standard Observer
λ	Wavelength (nm)
$\Delta\lambda$	Wavelength interval
$\beta_i(\lambda)$	Spectral reflectance of each test colour i
R_i	Special CRI of each test colour i
R_a	General CRI
Subscripts	
r	Reference illuminant
t	Transmitted illuminant
i	Enumeration of test colour 1 to 8

1. Introduction

Building-Integrated Semi-transparent Photovoltaic window (PV window) can be integrated in the building by replacing conventional glazing system. PV window, which is an innovative and emerging glazing technology for building application [1] [2] [3], can provide onsite energy generation and reduce building energy consumption to potentially regulate CO_2 emission [4]. When integrating different types of solar cells (e.g. amorphous silicon (a-Si) solar cells, Cadmium telluride (CdTe) thin film solar cells, Dye-sensitized solar cells etc.) into glazing unit to compose a semi-transparent PV window, the presence of solar cells and the solar cell covering ratio may significantly affect PV window electricity generation rate, indoor thermal environment, luminous environment and building energy performance. When solar radiation incidents on the surface of a semi-transparent PV window, part of the solar radiation is captured by these solar cells to generate electrical power, while part of the solar radiation penetrates into the indoor space through gaps between solar cells, allowing for passive heating and satisfaction of daylight needs. Increasing transparency (i.e. reducing solar cell covering ratio) of a semi-transparent PV window leads to a reduction of electrical generation, but more daylight is permitted to transmit through contributing to the indoor luminous environment. Zhang and Lu [5] have investigated the electrical and daylighting performance of three amorphous silicon (a-

Si) based semi-transparent PV window with different transparency (i.e. 10%, 16% and 26%) through numerical simulation. Results indicated that with the transparency of PV window increasing from 10% to 26%, the daylighting performance was significantly improved, while the annual electrical generation of PV window gradually reduced from 173 kWh to 132 kWh in Shanghai, China. Barman et al. [6] explored the energy performance of a one-floor building integrated with five types of CdTe PV windows with different transparency (i.e. from 6% to 27.5%) in Jaipur, India. Simulation results showed that the energy generation of CdTe PV window decreases with the increase of its transparency. Applying CdTe PV window with lowest and highest transparency (i.e. 6% and 27.5%) in the south orientation generated electricity of 119.6 and 74.74 kWh/m^2·year respectively. At the meantime, building energy consumption increases with the increasing of CdTe PV window transparency. The increment is mainly resulted by the dropping in energy generation and a slight increasing in cooling energy demand. Miyazaki et al. [7] have investigated the effect of a-Si PV windows with different transparency (i.e. from 10% to 80%) on building energy performance of an office located at Tokyo, Japan. It was found that although a-Si PV window with the lowest transparency (i.e. 10%) always generates the maximum amount of electricity. However, due to the energy consumption for artificial lighting is larger for the a-Si PV window with low transparency, the best building energy performance for the office is achieved when it is integrated with a-Si PV window with 80% transparency for WWR of 30%. The presence of solar cells also significantly affect the optical properties (e.g. spectral transmittance, light-scattering characteristics, etc.) of the window unit, resulting a distinct daylighting environment in a space served by them when compared with that of a normal double glazing. Therefore, in seeking to ensure a comfort luminous environment, evaluation of the daylighting performance of applying PV windows to buildings is increasingly required. The daylighting performance can be explored through two aspects via daylight quantity and daylight quality. For daylight quantity assessment, the metric of Daylight Factor (DF) is frequently formalised within national standards and widely employed by architects and designers [8-10]. This metric describes the ratio of internal illumination at a given point to external horizontal illumination [11]. The traditional method of acquiring DF is restricted to calculations based on an unobstructed CIE overcast sky. The recent development of this approach enables it to become applicable for 15 CIE standard skies[12] and takes into account building directions, solar positions and the effect of direct and reflected sunlight [13]. Once annual climate data is available for a selected location, climate-based metrics, such as Useful Daylight Illuminance (UDI) [14] and Daylight Autonomy (DA) [15], are able to provide more comprehensive, accurate and dynamic predictions of daylight availability while representing time varying daylight illuminance. It has seen an increasing number of studies that using this kind of climate-based dynamic metrics to investigate the daylight quantity of applying window integrated with PV modules in the literature [16-18]. Kapsis et al. [19] have investigated the potential impact of a semi-transparent photovoltaic module on the daylighting performance of an office building via dynamic simulation method. Annual spatial Daylight Autonomy, which was calculated based on simulation results, indicated that sufficient daylight for the office can be provided by the presence of semi-transparent photovoltaic module with 30% visible transmittance. Sun et al. [20] explored the dynamic daylighting performance of a cellular office of applying a CdTe PV window with the adoption of different window design scenarios under different climates (i.e. Harbin and Guangzhou) using RADIANCE. The UDI calculated based on simulation results indicated that designs with a large portion of the window area covered by PV window while keeping sufficient daylighting area provided the optimum daylight availability under the climate of Guangzhou, while covering the whole window area by PV window provided the optimum daylight availability under the climate of Harbin.

Daylight quantity is not the only factor that affects luminous environment of an indoor space. Velasco [21] states that glare, incorrect distribution of light density, low light colour quality may also exist as potential risks that can negatively affect human visual comfort in terms of human health, mood, activity and work efficiency [22]. These factors (e.g. glare, daylight distribution and daylight colour quality) determine indoor daylight quality. Glare is a crucial criteria in the occupant visual comfort evaluation, which describes the situation where the luminance fall in the field of view is more than the brightness to which eyes are adapted. Glare shall be limited as the appearance of glare can result in errors, fatigue and accidents. The daylight glare metric named Daylight Glare Probability (DGP), which was introduced by Wienold and Christofferen [23] in 2006, has become the preferred metric for assessing glare for the luminous environment in many research [24-26]. Glare has been considered in a number of visual comfort evaluations for building integrated with PV window. Cannavale [27] carried out the daylight glare evaluation for a hypothetical test-room that equipped with PV window, commercial solar control glass and a clear glass through simulation. It was found that the occurrence of high DGP can be significantly reduced by PV window which was outperformed both solar control glass and clear glass. The daylight spatial distribution is another factor considered in the daylight quality evaluation. Uniform daylight spatial distributions will promise occupants to perceive the luminous environment continuously and without sudden breaks caused by illuminance level drops. Uniformity metrics include illuminance uniformity ratio (UR) defined by standard IBSE guide A [28] and illuminance uniformity (U_O) specified by BS EN 12464 [29]. They have been applied in the research of daylight uniformity exploration [30, 31]. Zomorodian [32] have carried out the dynamic simulation for the evaluation of daylight distribution for applying window with different configuration. The result was analysed by U_O, which indicated that lighting uniformity would reduce with the increasing of window-head-height and decreasing of windowsill. Other than daylight glare and distribution uniformity, colour quality of the transmitted daylight is equally important when assessing the indoor luminous environment. This will affect the colour appearance of a space which will contribute to the psychological and physical well-being of the occupants. CIE BS EN 12464-1 [29] recommended two metrics to characterize the colour qualities of a light source (i.e. both artificial light source and daylight transmitted through windows). They are Correlated Colour Temperature (CCT) and Colour Rendering Index (CRI) [33]. These two metrics have a few implementations for evaluating the colour quality of daylight modified by different PV windows [34-36]. Nandar et al. [37] investigated the colour quality of the daylight passing through different types of semi-transparent photovoltaic (i.e. with 20%, 30%, 40% and 50% transparency respectively) by analysing CCT and CRI based on measured spectral transmittance of the selected PVs. It is shown that the modules in neutral a-Si-colour presents excellent colour rendering, but the modules in red and blue colour shown a weak colour rendering capacity with CRI less than 90. Ghosh et al. [38] evaluated the colour quality of the light transmitted through multi-crystalline based semi-transparent Photovoltaic-vacuum glazing. They found that the semi-transparent PV-vacuum glazing with transparency 35% and 42% offered higher allowable CCT and CRI than those of 30% and 40% transparent states of suspended particle device glazing, respectively.

Although, in the literature, efforts have been made to evaluate daylight performance of applying PV windows for each individual aspects (i.e. daylight availability, glare, daylight distribution and colour quality), to the best of the authors' knowledge, systematic and holistic investigations accounting all the aspects that may affect the luminous environment has not been seen. In practice, this information can be used by construction professionals to ensure that PV windows are designed appropriately and applied correctly. Thus, a comprehensive daylight performance evaluation in terms of daylight quantity (i.e. daylight availability) and daylight quantity (i.e. glare, daylight distribution and colour quality) for the building integrated PV window is necessarily needed.

This paper provides a comprehensive assessment on daylight performance when applying semi-transparent PV windows to buildings through a holistic consideration of daylight quantity and daylight quality. Window integrated thin film CdTe solar cells with four transparency were investigated to understand the influence of their transparency on the overall daylight performance. RADIANCE are used to predict the dynamic daylight availability, uniformity and glare probability of applying these four CdTe PV windows to an office with different window to wall ratio under a climate of Birmingham, UK. Useful Daylight illuminance (UDI) is used as the metric to evaluate daylight quantity while metrics of Illuminance Uniformity (U_O) and Daylight Glare Possibility (DGP) are used to assess daylight quality in terms of homogeneity of daylight distribution and glare. The measured spectral properties of these four CdTe PV windows are used to calculate the colour quality of the transmitted light under three different daylight scenarios. Metrics of Correlated Colour Temperature (CCT) and Colour Rendering Index (CRI) are then used to quantify their colour quality.

2. Daylight performance assessment metrics

Daylight quantity metric, UDI, as well as daylight quality metrics, U_O and DPGs, which are obtained based on dynamic annual simulation, are summarized as follow. CCT and CRI, which encompass the colour quality of transmitted light for daylight quality evaluation, are also specified as follow.

- Useful Daylight illuminance (UDI)

UDI, which is developed by Nabil and Mardaljevic [14], is widely used by a number of researchers for accounting climate-based analyses of daylight availability [39, 40]. It is different from conventional static metrics (e.g. daylight factor), which only result a single value under a specific condition. UDI describes the illuminance level on each point considered for each daylight hour through a course of a year. This is calculated by dividing hourly illuminance into three bins within a year. The three bins include the undersupply bin ($UDI_{100\ lux}$, where illuminance <100 lux), useful illuminance bin ($UDI_{100\text{-}2000\ lux}$, where 100 lux ≤ illuminance ≤ 2000 lux) and oversupply bin ($UDI_{2000\ lux}$, where illuminance > 2000 lux). Considering the most desirable illuminance range for a typical office is 500 lux-2000lux [41], the useful illuminance bin ($UDI_{100\text{-}2000\ lux}$) can be further subdivided at a threshold of 500 lux. The most desirable bin ($UDI_{500\text{-}2000\ lux}$) means the daylight illuminance is sufficient as the sole source of illumination [42].

- Daylight illuminance uniformity (U_O)

The homogeneity of indoor daylight distribution can be evaluated by U_O, which is obtained using the minimum illuminance divided by the average illuminance. In this research, the minimum U_O on the task area within a cellular office was investigated. According to BS EN 12464 [29], if the office is used for filing, copying, etc., the minimum U_O on the task area should be higher than 0.4. If it is used for writing, typing, reading or data processing, the recommended minimum U_O on the task area is 0.6. If it is used for technical drawing, the required minimum U_O on the task area is 0.7. According to the recommended minimum value, U_O is divided into four acceptance bins which are $U_O \geq 0.4$, $0.4 < U_O < 0.6$, $0.6 > U_O > 0.7$ and $U_O \geq 0.7$.

- Simplified Daylight Glare Probability (DGPs)

DGP, which was proposed by Wienold and Christoffersen [23], is the most recent index used to evaluate glare from daylight. The prediction of annual dynamic DGP requires a significant computational overhead which may be highly time consuming. Therefore, a simplified DGP is obtained only based on vertical illuminance [43]. DGPs thresholds classify the glare probability caused by daylight into four levels: 1) DGPs ≤ 0.35 is considered as imperceptible glare; 2) DGPs between 0.35-0.4 is perceptible glare; 3) DGPs between 0.4-0.45 is disturbing glare; and 4) DGPs ≥ 0.45 is intolerable glare. Wienold [43] defined 4 glare comfort classes for luminous environment. They are: 1) if the period for imperceptible glare (i.e. DPG ≤ 0.35) is over 95% of working hours in an office, the acceptance of glare has a 'Best' classification; 2) if the period for perceptible glare (i.e. DPG < 0.4) is over 95% of working hours, the classification for acceptance of glare is 'Good'; 3) if the period for disturbing glare (i.e. DPG < 0.45) is over 95% of working hours, the classification for acceptance of glare is 'Reasonable'; and 4) the 'Unreasonable' classification of acceptance of glare is defined when the period for intolerable glare (DGPs ≥ 0.45) is over 5% of working hours.

- Correlated Colour Temperature (CCT)

Colour appearance of a light source can be quantified by correlated colour temperature (CCT). CCT, which is usually given in degrees Kelvin (K), is a one-dimensional description of the colour of near-white light sources. Defining the colour appearance of a light source using the temperature on the blackbody locus that most closely resembles the light source's chromaticity coordinates in the CIE chromaticity diagram is named as Correlated Colour Temperature (CCT) [44]. A low CCT indicates the light is reddish, a high CCT is bluish-white and the light with the middle range of CCT will present neutral colour. It has been recommended that a preferred transmitted daylight should have CCT within the range between 3000K-7500K [35]. It means if CCT of transmitted daylight falling in this range, colour appearance of the transmitted daylight is classified to the best.

- Colour Rendering Index (CRI)

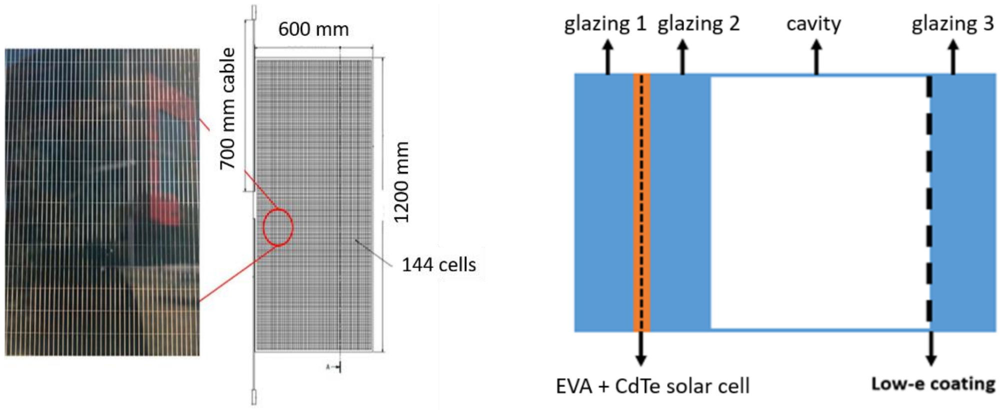
CRI can be used to characterize colour rendering properties of the transmitted light. This describes how well the transmitted light renders a set of colour samples relative to their rendering under a reference illuminant. 14 test colour samples are specified by CIE 1995 [45] for colour rendering evaluation as shown in Table 1. The front eight test colour samples cover the hue circle, are moderate in saturation and have similar lightness [46]. The rest six test colour samples contain the saturated red, yellow, green and blue, and complexion and foliage colours. The colour rendering capacity of light source for each test colour sample can be evaluated by specific CRI (Ri). The average of the special CRIs for the front eight test colour samples is defined as general CRI (Ra).). It has been recommended by BS EN 1246-1 [29] that the minimum acceptable Ra is 80. Ra higher than 90 is considered as a good indication of colour rendering for luminous environment [37], while Ra higher than 95 is considered as a best colour rendering indication [47]. Accordingly, colour rendering of light is classified into four ranks. They are 'Best' (where $Ra \geq 95$), 'Good' (where $95 > Ra > 90$), 'Reasonable' (where $90 > Ra > 80$) and 'Unreasonable' (where $Ra \leq 80$).

No.	Colour appearance under daylight	No.	Colour appearance under daylight
R1	Light greyish red	R9	Strong red
R2	Dark greyish yellow	R10	Strong yellow
R3	Strong yellow green	R11	Strong green
R4	Moderate yellowish green	R12	Strong blue
R5	Light bluish green	R13	Light yellowish pink (human complexion)
R6	Light blue	R14	Moderate olive green (leaf green)
R7	Light violet		
R8	Light reddish purple		

Table 1 CIE test colour samples.

3. Research methodology

The daylight quantity and daylight quality of CdTe PV window have been comprehensively investigated using an incorporative method including numerical simulation (RADIANCE) and experimental test to explore its implementation. The tested windows with integrated CdTe solar cell includes four types: CdTe-20%, CdTe-30%, CdTe-40% and CdTe-50%. Each percentage indicates the proportion of transparent area (i.e. area that not covered by solar cells) over the overall glazing area. The CdTe PV window sample is shown in Fig.1. (a) [20], it can be seen that CdTe solar cells are opaque and spaced properly in order to attain the required level of transparency and outdoor views. The configuration of a typical CdTe PV window is shown in Fig. 1 (b). The properly placed CdTe solar cells are encapsulated between ethylene vinyl acetate (EVA) films and sandwiched between two clear glazing panes (glazing 1 and glazing 2 in Fig. 1 (b)). The other layer is a low-e coated glazing pane (glazing 3 in Fig. 1 (b)). The cavity between glazing 2 and glazing 3 is 20mm and filled with Argon. A normal clear glazing was also tested as a reference window for comparison.



(a) (b)

Fig.1. (a) CdTe PV window sample (b) Configuration of CdTe PV window.

3.1. Overview of the analysis method

The comprehensive evaluations of building daylight performance for CdTe PV windows were based on attaining a balance between daylight quantity and daylight quality. As shown in Fig. 2, daylight quantity evaluation was analysed using dynamic metric, UDI. Daylight quality evaluation was carried out in terms of daylight glare, daylight spatial distribution and light colour quality. Daylight glare was assessed by DGPs and daylight spatial distribution was indicated by U_O. The dynamic metrics UDI, DGPs and U_O were determined based on the hourly daylight illuminance predicted by RADIANCE simulation. The colour quality can be assessed by metrics of CCT and CRI. These can be acquired through CIE standard calculation which was carried out based on the measured spectral transmittance of CdTe PV windows. Detailed information of the research methodologies can be found in next sections.

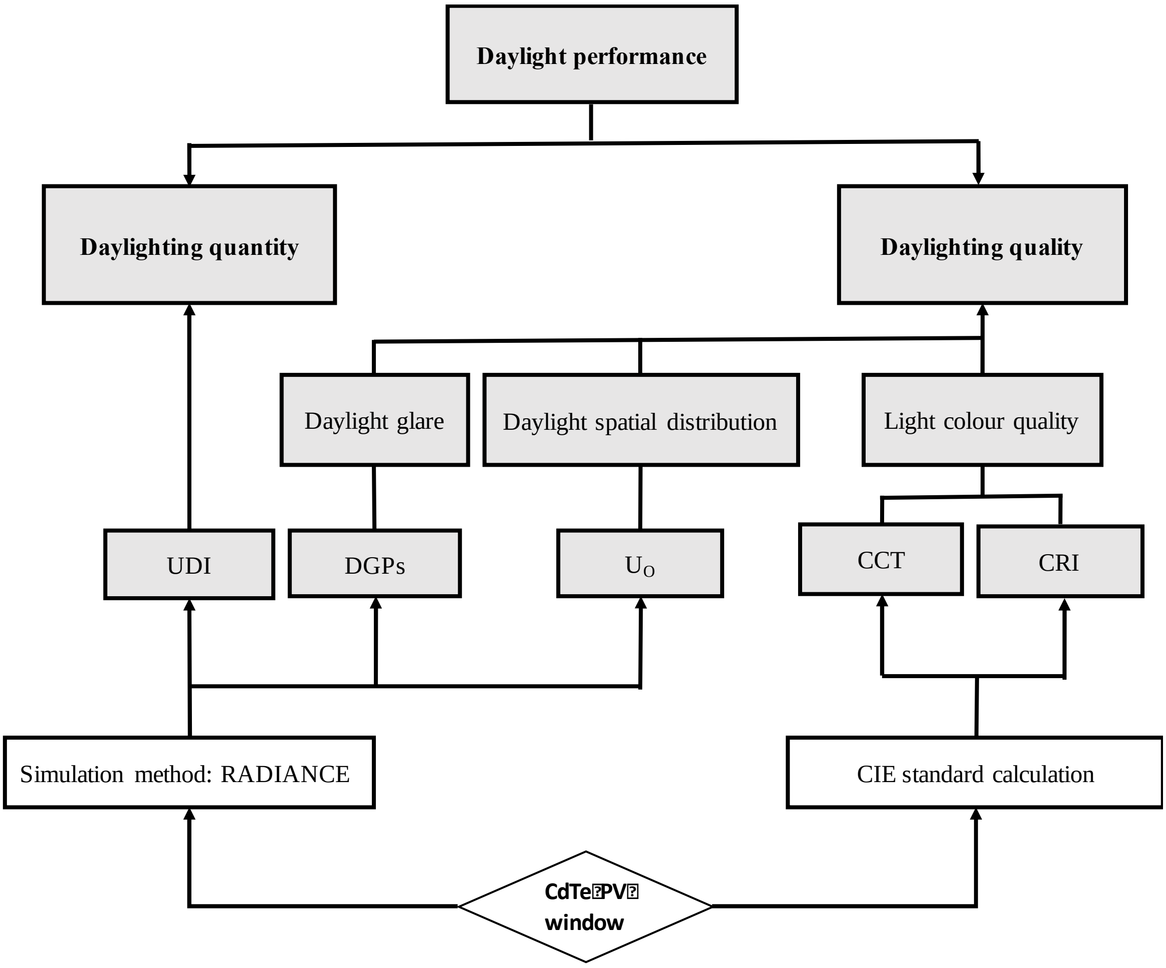


Fig. 2 Flowchart of modelling and calculating daylighting performance for CdTe PV window. In this Fig., white rectangles indicate the daylight performance processing methods. Grey rectangles represent the expected daylight performance metrics' values from the related processes.

3.2. Simulation methods for UDI, DGPs and U_O acquiring

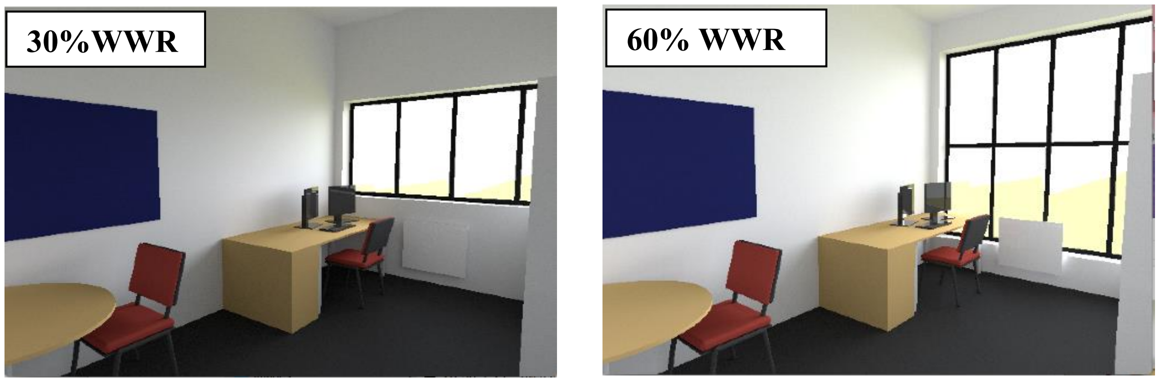
The three daylight performance metrics UDI, DGPs and U_O were obtained based on annual hourly simulation results from RADIANCE which is a research-grade simulation tool and has been validated by several studies [48-50]. Due to the configuration of the CdTe PV window, multiple inter-reflection will occur when daylight passes through it. For describing such a window system in RADIANCE, the complex interactions within the CdTe PV window were substituted by a pre-calculated transmission matrix (T). The light passing from sky to the external surface of the window and the light passing from interior surface to the viewpoint were described by the daylight matrix (D) and view matrix (V) respectively. As the office information, including the surrounding environment, orientation, office geometry, furniture and all the surface properties, was input, the daylight matrix (D) and view matrix (V) can be generated. The combination of the three matrices (T, D and V) used to describe light path is called "Three-phase method", which was employed in this research to carry out the annual daylighting simulation for CdTe PV window. The corresponding equations are given as follow:

$$i = VDT\ s \quad (1)$$

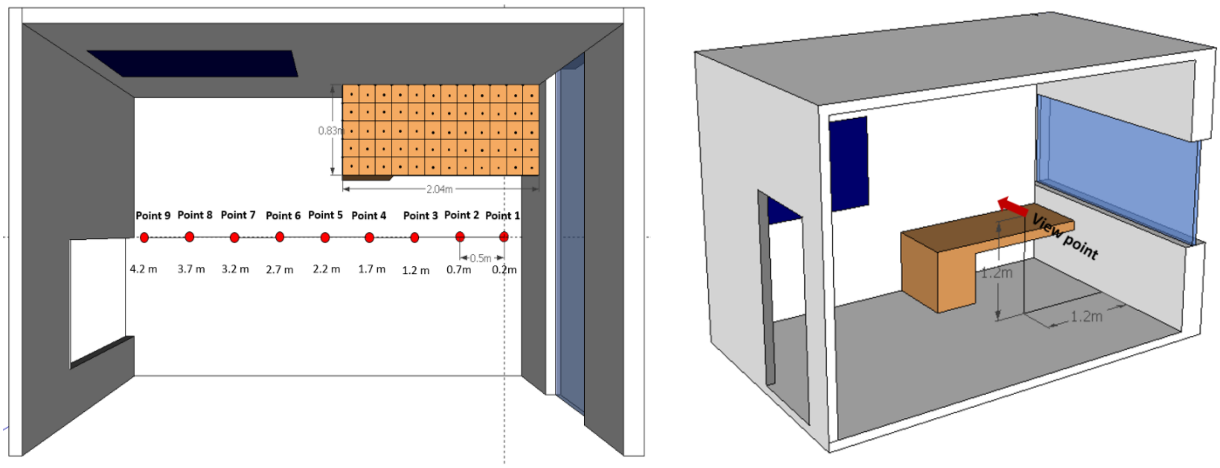
$$I = VDTS \quad (2)$$

Illuminance or luminance at any point of interest for a single time step (i) or for a time series (I) can be obtained from the simulation results. The sky condition for a single time step or a time series was represented by sky vector (s) or sky matrix (S) which was converted from IWEC (International Weather for Energy Calculation) weather data of Birmingham. Transmission matrix (T) for CdTe PV window was expressed with BSDFs which was generated from a ray-tracing program named genBSDF in RADIANCE. In the BSDF file, light from each exterior direction was allocated to each interior direction and the corresponding allocated light was defined by coefficients. Therefore, the optical properties of each CdTe PV window can be accurately described.

The simulation model is a south-faced cellular office with dimensions of 2.9 m (width) × 4.4 m (depth) × 3.3 m (height). In this research, 60% WWR and 30% WWR were selected to investigate the daylight performance of the CdTe PV window, while the corresponding window dimension is 1.3 m (height) × 2.65 m (width) and 2.6 m (height) × 2.65 m (width) respectively, as shown in the renderings Fig. 3 (a) and (b). Visible reflectance of the purely diffused office surfaces were 30% (floor), 80% (walls) and 80% (ceiling) respectively. It was assumed that there are no any obstructions outside the office, such as surrounding buildings and vegetation. For the daylight quantity evaluation, nine calculated points on office working plane (with 0.75 m height) were set alone the central line of the office from window to the end wall. The distance between each calculated point is 0.5m, while the first point is 0.2 m away from the window position in the horizontal direction as shown in Fig. 3 (c) (indicated by red points). The surface of the desk with dimensions of 0.83 m (width) × 2.04 m (length) was determined as the task area for the uniformity evaluation. An illuminance grid on the task area was determined to indicate the points at which the illuminance value was calculated for U_O evaluation as shown in Fig. 3 (c). The dimension of grid cells, which is 0.166m × 0.17 m, satisfied the requirement of BS EN 12464 [29] on the aspect ratio of the grid cell.-The office is designed for the people who positioned near the window. Therefore, the glare evaluation is carried out with considering that the location of the view point is 1.2m away from the window and 1.2 m above the floor on the centre axis of the room while the observer facing the desk as indicated in Fig. 3 (d). A validated RADIANCE model has been used for this work [40].



(a) (b)



(c) (d)

Fig. 3. (a) Rendered image with 30% WWR (b) Rendered image with 60% WWR (c) Selected points (red) for UDI calculation and selected points for daylight distribution calculation (black) (d) The selected view point for DGPs calculation.

3.3. Experimental measurement and calculation process for CCT and CRI acquiring

Correlated colour temperature (CCT) and colour rendering index (CRI) are the two commonly used metrics to characterise the colour quality of the transmitted daylight for a window application. The CCT and CRI can be calculated based on measured spectral transmittance of CdTe PV window.

3.3.1. Spectral transmittance measurement

The spectral transmittances for CdTe windows and clear double glazing over the wavelength range of 380-780 nm were tested using the instrument demonstrated in Fig. 4. OceanOptics HL2000 light was used as the light source. The light source perpendicularly transmitted through the tested PV window, which is fixed closely on the port of a transmittance integrating sphere (FOIS-1). All the transmitted lighting in the forwards direction has been collected by the integrating sphere. The spectrometer (OceanOptics VIS-NIR-ES spectrometer) used to measure the spectral transmittance of the collected light, while the measurement results are shown in Fig.5. The clear double glazing has a low transmittance in wavelength range of 600nm-700nm, while has a relative high transmittance in the wavelength range of 400nm-500nm. Differ from clear double glazing, CdTe PV windows show relative high spectral transmittance in the wavelength range of 600nm-700nm.

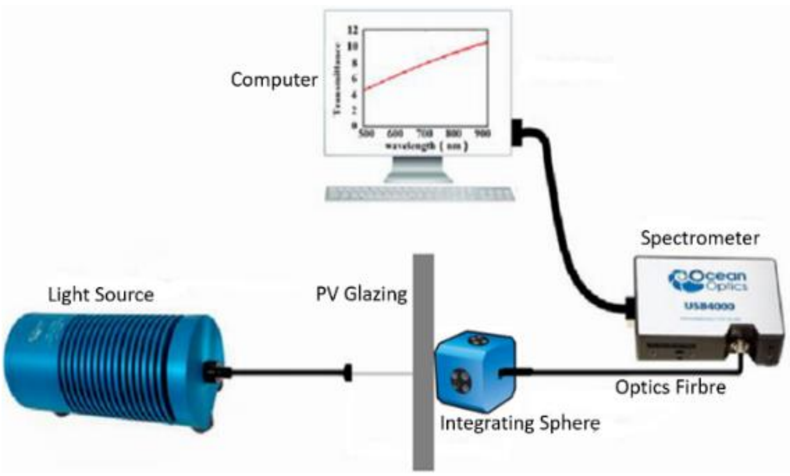


Fig.4. CdTe PV window spectral transmittance measurement.

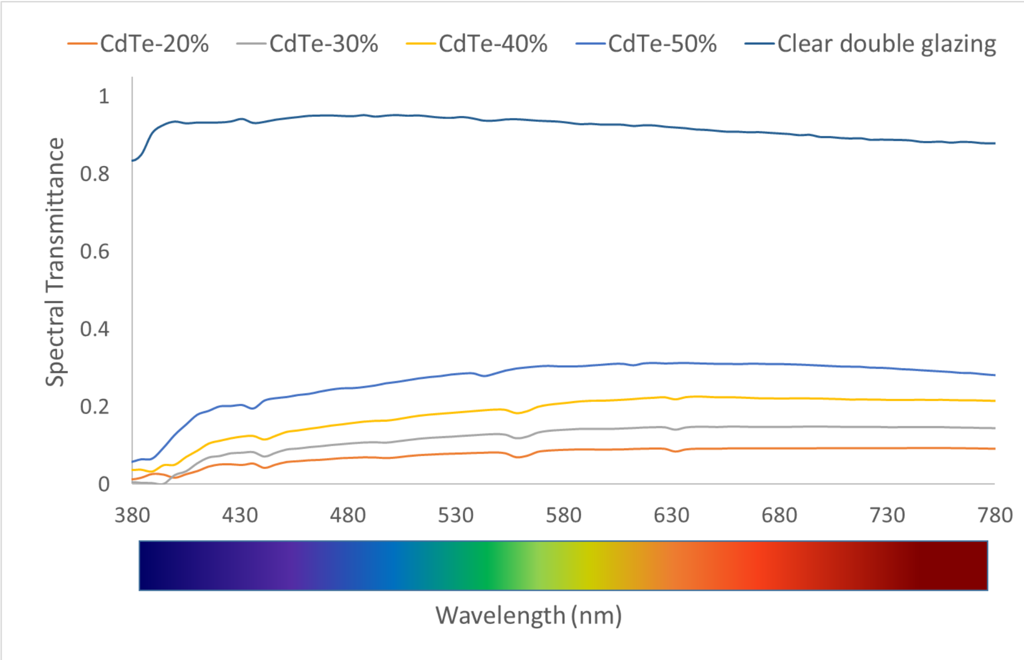


Fig.5 Spectral transmittance of CdTe PV windows and clear double glazing

3.3.2. Calculation process

Three CIE standard daylight illuminants with CCT of 4000K, 6500 K and 25000K, representing three different daylight scenarios, are commonly used to embody weak daylight in the early morning, normal overcast daylight and extreme summer daylight respectively [51] [52]. They were selected in this study to evaluate the CCT and CRI for these CdTe PV windows. The acquirement process of CCT for daylight transmitted through each CdTe PV window is given in equation (3-9) [53]:

$$\mathrm{X}_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\tau(\lambda)\,\bar{x}(\lambda)\Delta\lambda \tag{3}$$

$$\mathrm{Y}_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\,\tau(\lambda)\bar{y}(\lambda)\Delta\lambda \tag{4}$$

$$\mathrm{Z}_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\,\tau(\lambda)\bar{z}(\lambda) \tag{5}$$

$$\mathrm{x} = \frac{X}{X+Y+Z} \tag{6}$$

$$\mathrm{y} = \frac{Y}{X+Y+Z} \tag{7}$$

$$\mathrm{n} = \frac{x-0.3320}{0.1858-y} \tag{8}$$

$$\mathrm{CCT} = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \tag{9}$$

where, X, Y and Z are the tristimulus values that used to describe the colour of the transmitted light based on human visual reaction, which are defined in the CIE 1931 chromaticity diagram. $SPD(\lambda)$ is the spectral power distribution (SPD) of the three CIE standard daylight scenarios (i.e. daylight illuminants with CCT of 4000K, 6500K and 25000K). $\tau(\lambda)$ is the spectral transmittance of the four types of CdTe PV window. $\bar{x}\bar{y}\bar{z}$ are the CIE standard colour-matching functions for the CIE 1931 2º Standard Observer. $\Delta\lambda$ is the wavelength interval.

For calculating CRI, CIE 1931 tristimulus values (XYZ) of reference illuminant and test illuminant that reflected by tested colour samples were determined firstly. XYZ of each group was transformed into 1964 colour space $W^*, U^*, V^*$by considering chromatically adaptation transform. The resultant colour shift (ΔE_i) is determined by calculating the colour difference between the eight-tested colour samples that illuminated under reference illuminant and that under test illuminant. Specific colour rendering index (R_i) is calculated for these tested colour samples based on the ΔE_i of each colour respectively. R_a is the arithmetical mean of the eight colour samples. Those are derived by equation (10-15):

$$X_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\tau(\lambda)\,\beta_i(\lambda)\bar{x}(\lambda)\Delta\lambda \tag{10}$$

$$Y_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\,\tau(\lambda)\beta_i(\lambda)\bar{y}(\lambda)\Delta\lambda \tag{11}$$

$$Z_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\,\tau(\lambda)\beta_i(\lambda)\bar{z}(\lambda) \tag{12}$$

$$\Delta E_i = [\left(U^*_{r,i} - U^*_{t,i}\right)^2 + \left(V^*_{r,i} - V^*_{t,i}\right)^2 + \left(W^*_{r,i} - W^*_{t,i}\right)^2]^{1/2} \tag{13}$$

$$R_i = 100 - 4.6\Delta E_i \tag{14}$$

$$R_a = 1/8 \sum_{i=8}^{8} R_i \tag{15}$$

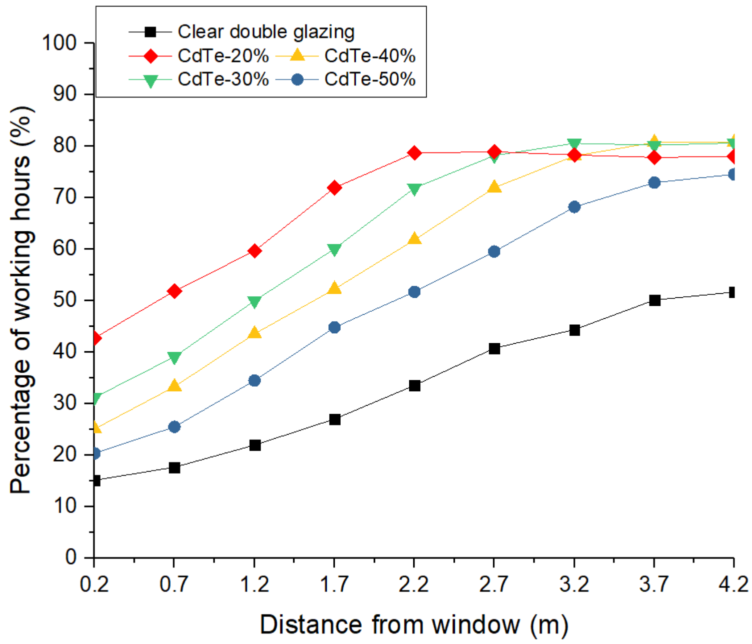
where, $\beta_i(\lambda)$ is the spectral reflectance of each test colour. U*, V*, W* are the coordinates in the CIE 1964 (U*, V*, W*) colour space, which can be transferred from the tristimulus values. ΔE is the colour difference. R_i is the specific colour rendering index. R_a is general colour rendering index.

4. Result and discussion

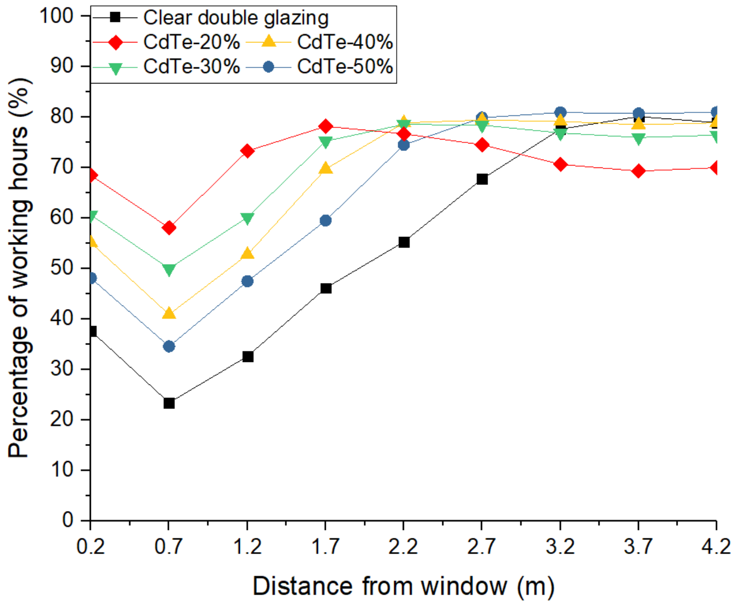
4.1. Daylight quantity: Useful Daylight Illuminance (UDI) for CdTe PV window

Two range of useful illuminance bin range from 100 to 2000lux (wide range) and 500 to 2000lux (comfortable range) were studied. The obtained UDIs for working hours from 8:00 to

17:00 for the central line from the window to the end wall for the cellular office are illustrated in Figs. 6 and 7, respectively. Fig 6 (a) and (b) shows UDI in a wider useful illuminance bin range from 100 to 2000lux with 60% and 30% WWR, respectively. From Fig 6 (a), it can be seen that when WWR is 60%, significant improvement over clear double glazing is achieved by the presence of semi-transparent CdTe PV windows. For example, useful illuminance is in the range from 15% to 52% for double glazed window and 20% to 75% for CdTe-50% along the central line from the window to the end wall. CdTe-20% delivers the best daylighting performance, it has a $UDI_{100\text{-}2000lux}$ in the range from approximately 43 to 78%. For CdTe-30% and CdTe-40%, percentage of working hours for illuminance falling in the range of 100-2000 lux is 31%-81% and 25%-81% respectively. Both of them are better than that of CdTe-50%, but less than CdTe-20%. The $UDI_{100\text{-}2000\ lux}$ for all window with 30% WWR are shown in Fig. 6 (b). It can be seen that the CdTe PV windows can improve the $UDI_{100\text{-}2000\ lux}$ when compared with that of the clear double glazing in the range from the window to a distance of 2.7m away from it. However, there is no significant improvement for the CdTe windows in a distance above 2.7m away from the window, especially for CdTe-20%, CdTe-30% and CdTe-40%. Considering the most desirable illuminance range for a typical office is 500 lux-2000 lux [41], the most desirable bin in the range from 500 to 2000 lux ($UDI_{500\text{-}2000\ lux}$) was further analyzed for CdTe PV window shown in Fig. 7. From Fig. 7(a) it can be seen that with a 60% WWR, CdTe PV windows other than CdTe-20% can provide an improved daylight performance when replacing the clear double glazing. However, when WWR is reduced from 60% to 30% as shown in Fig. 7 (b), the daylight performance of CdTe PV windows become undesirable, while significant reduction of desirable daylight in the region of the room close to the end wall can be observed. For example, the percentage of working hours in $UDI_{500\text{-}2000\ lux}$ for CdTe-20% is over 10% to 50% lower than that of clear double glazing at the distance from 2.2 m to the end wall. It can also be seen that the $UDI_{500\ –\ 2000\ lux}$ is at least approximately 10% lower than the $UDI_{100\ to\ 2000\ lux}$. This might be explained that there are more hours of the illuminance within the range from 100 to 500 lux.

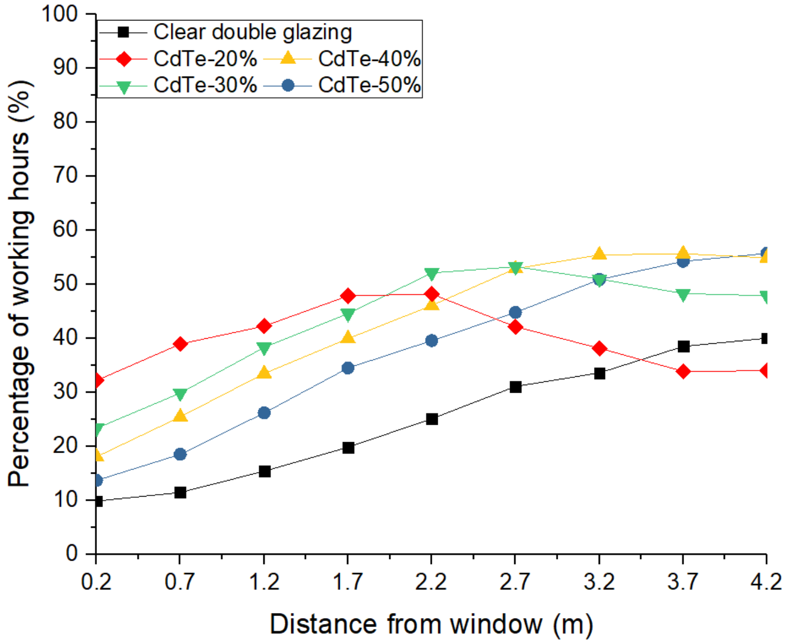


(a)

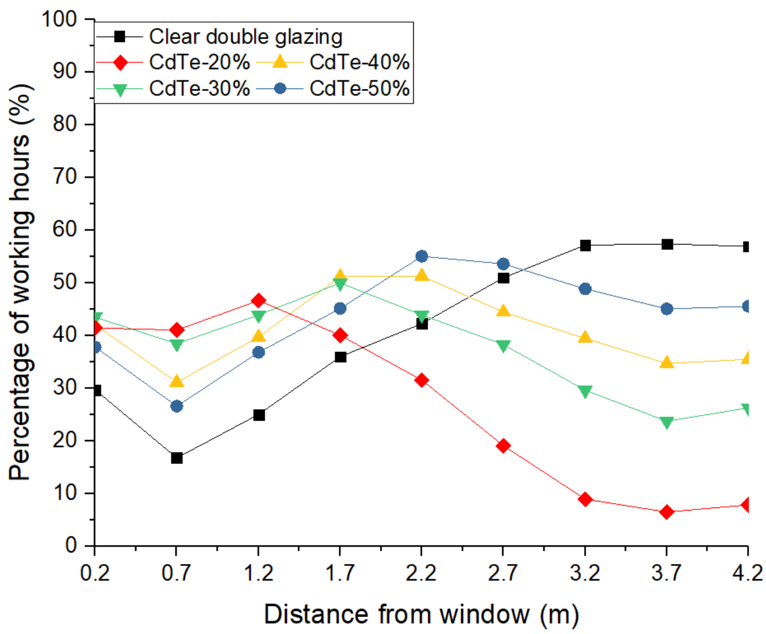


(b)

Fig. 6. $UDI_{100\text{-}2000lux}$ bin at points along the central line from window to end wall with the four types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR (b) 30% WWR.



(a)



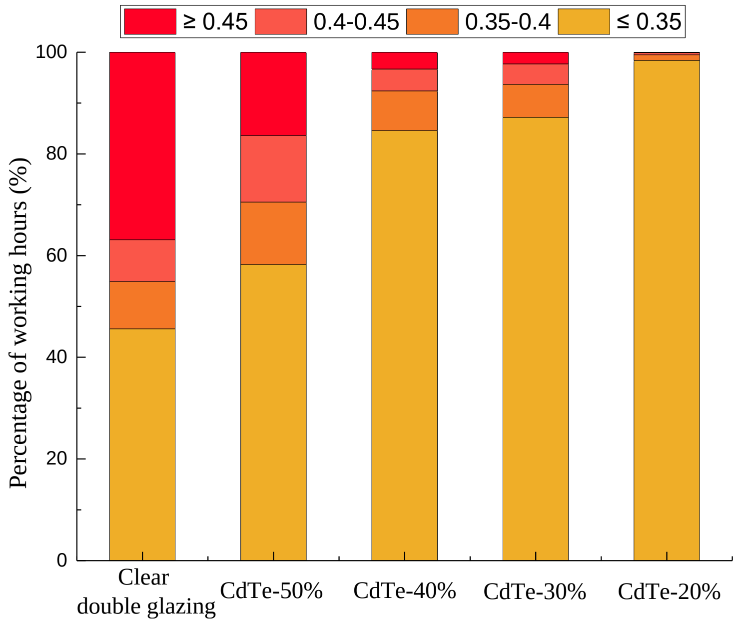
(b)

Fig. 7. $UDI_{500\text{-}2000lux}$ bin at points along the central line from window to end wall with the four types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR (b) 30% WWR.

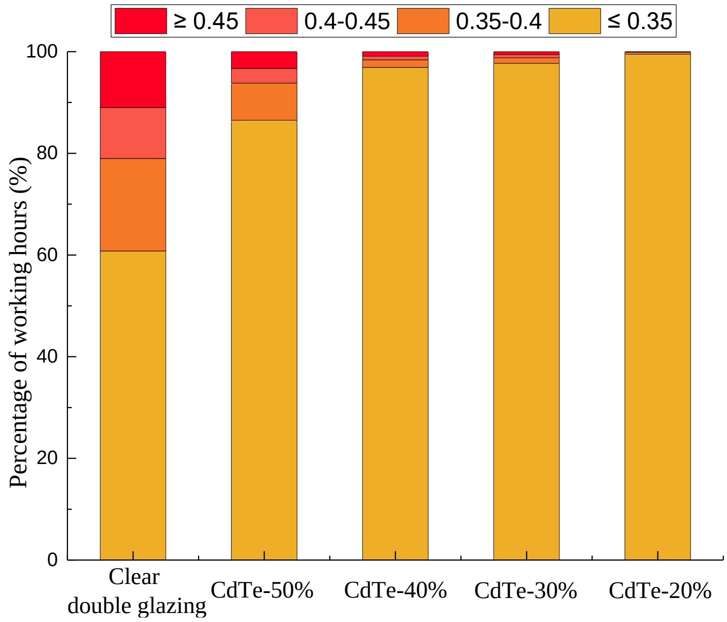
4.2. Daylight Quality

4.2.1. Daylight glare: simplified daylight glare probability (DGPs) for CdTe PV window

The obtained DGPs for the selected semi-transparent CdTe PV windows and the clear double glazing under WWR of 60% and 30% are shown in Fig. 8. DGPs is calculated by assuming the occupant position which is 1.2m away from the window at a 1.2 m height. When replacing the clear double glazing window with the CdTe PV window, the DPG can be significantly improved. For WWR of 60%, as shown in Fig. 8 (a), it can be seen that when CdTe-20% is applied, the acceptance of glare has 'Best' classification, as imperceptible glare (i.e. DPG ≤ 0.35) is over 95% of working hours. CdTe-30% and CdTe-40% offer 'Good' classification, the period for perceptible glare (i.e. DPG < 0.4) is over 95% of working hours. CdTe-50% and clear double glazing however, are classified to be 'Unreasonable', as intolerable glare (DGPs ≥ 0.45) is over 5% of working hours. Under the 30% WWR as shown in Fig. 8 (b), CdTe-20%, CdTe-30% and CdTe-40% PV windows provide the 'Best' classification and CdTe-50% offers the 'Good' classification for the acceptance of glare. When clear double glazing is applied, the acceptance of glare is classified to be 'Unreasonable'.



(a)

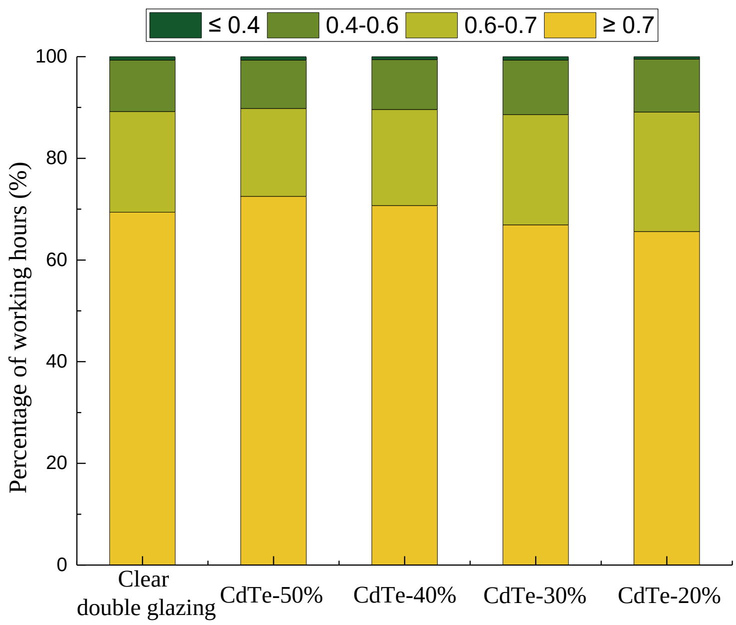


(b)

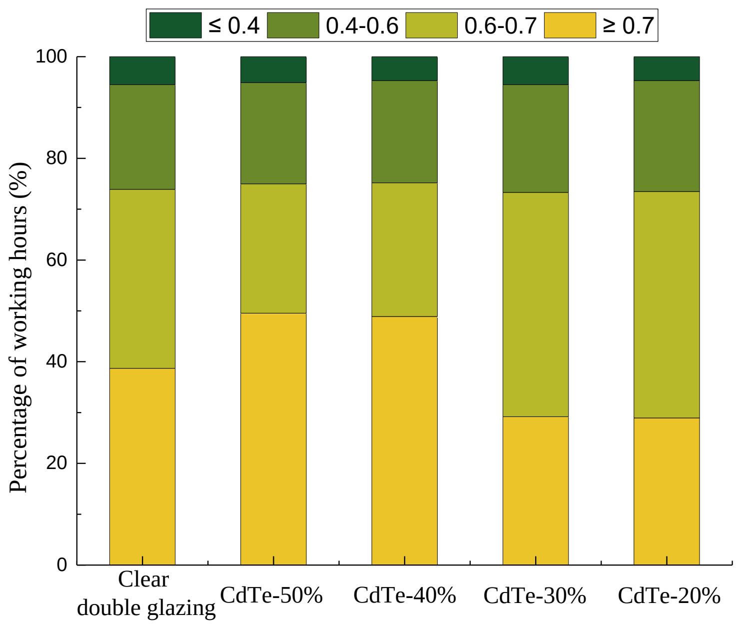
Fig. 8. DGPs of the four types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR (b) 30% WWR

4.2.2. Daylight distribution: Illuminance uniformity (U_O) for CdTe PV window

Annual predictions of the U_O on the task area of the office for both the clear double glazing and CdTe PV windows were conducted under 60% and 30% WWR respectively (as illustrated in Fig. 9). Under 60% WWR as shown in Fig. 9 (a), no significant improvement can be observed by replacing clear double glazing with CdTe PV windows. When WWR is changed from 60% to 30% as indicated in Fig. 9 (b), it can be seen that CdTe-50% and CdTe-40% show the best performance in daylight uniformity at 30% WWR. The clear double glazing is advanced than the CdTe-30% and CdTe-20% For example, the percentage of working hours for U_O in the range ≥ 0.7 for CdTe-50% and CdTe-40% is approximately 10% and 11% higher than that of the clear double glazing, respectively. When using CdTe-30% and CdTe-20% to replace clear double glazing, U_O in the range ≥ 0.7 is approximately 9% and 10% lower, respectively. Generally, CdTe PV windows under 60% WWR deliver better daylight performance in terms of illuminance uniformity than that under 30% WWR.



(a)



(b)

Fig.9 U_O on the task area with the four types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR (b) 30% WWR.

4.2.3. Colour quality of transmitted daylight

- *Correlated Colour Temperature for CdTe PV window (CCT)*

Fig. 10 shows the variation of CCT of the transmitted light through the four types of the CdTe PV windows and also the clear double glazing under three daylight scenarios. For the 4000K and 6500K daylight scenarios, clear double glazing has negligible influence on CCT. When the CdTe PV windows are applied, there is a reduction in CCT in the range between approximately 10%-26% depending on the type used. It can be clearly seen that the colour appearance of daylight transmitted through CdTe PV window is classified to be the 'Best' under both 4000K and 6500K daylight scenarios, due to CCT falling into the recommended comfortable range (i.e. within 3000K-7500K). In the scenario of extreme daylight in summer time where the CCT is 25000K, there is an approximately 20% reduction in the CCT for the clear double glazing, the CdTe PV windows offer a reduction from approximately 57% to 65% depending on the type applied. Although the CCT for the CdTe PV window is still high than 7500K, above the upper limit of the comfortable range, it provides a better potential to regulate the transmitted light to a better CCT than that of the clear double glazing.

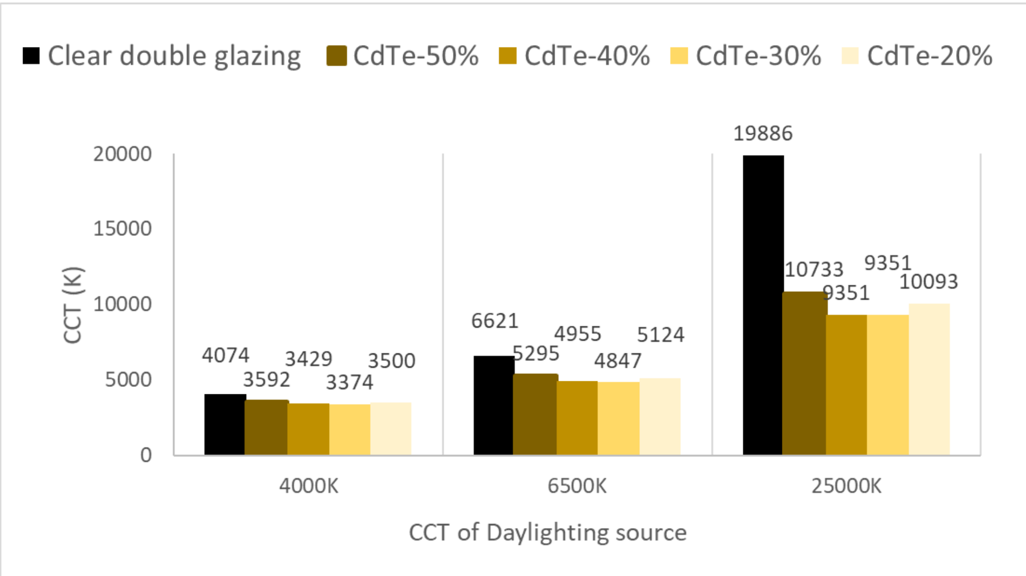
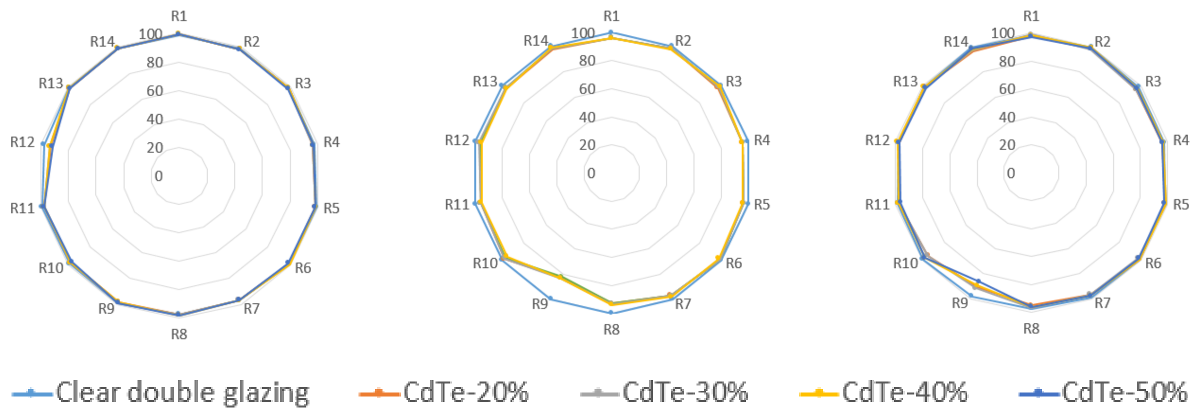


Fig. 10. CCT of transmitted light for CdTe PV window and clear double glazing under three daylight scenarios

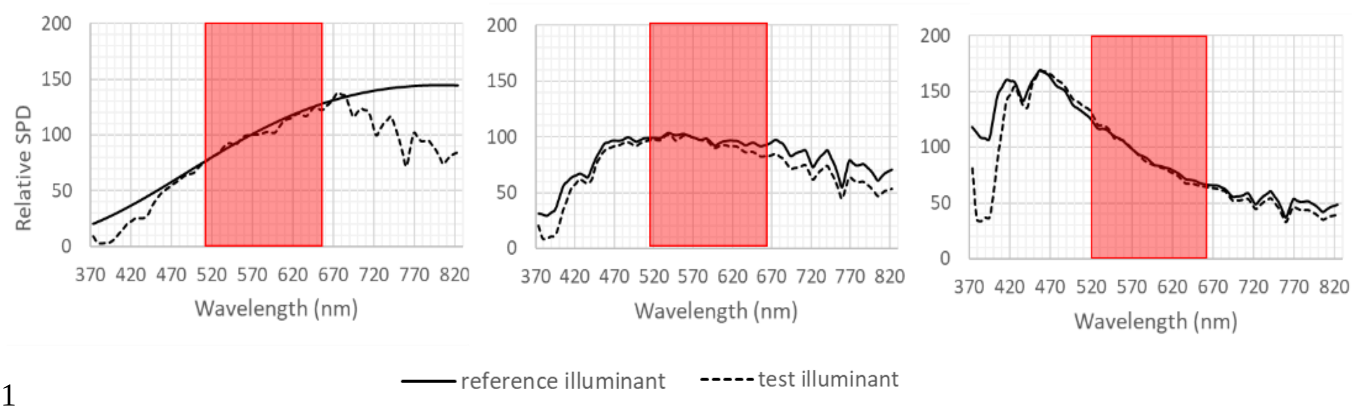
- *Colour Rendering Index (CRI) for CdTe PV window*

To explore the colour rendering properties of the CdTe PV windows, Ri for the 14 standard test colour samples (R_1 to R_{14}) of CdTe PV window and clear double glazing are plotted into radar charts under three daylight scenarios as shown in Fig. 11. From Fig. 11, it can be seen that for all the three scenario, clear double glazing and CdTe PV windows can achieve a CRI higher than 95 for the front eight-test colour (R_1 to R_8). It is also found that under the 6500K daylight scenario, CdTe PV window has relative poor ability to render R_9 (strong red) as the CRI of CdTe PV windows for R_9 are all below 85 under 6500K daylight. According to Lin et al. [54], the spectral power distortion of the test illuminant in the wavelength range between 520nm-665nm has significant effect on the CRI value for R_9. Fig. 12 shows the relative SPD of the test illuminant for CdTe-50% and the corresponding relative SPD of reference illumiant under three daylight scenarios. The largest deviation of relative SPD between test and reference illuminant within the 520 -665 nm (as highlighted with red block on the Fig. 12) can be observed in the 6500K scenarios. It explains why under 6500K daylight, the colour rendering capacity of CdTe PV window on the R_9 (strong red) is weaker than them under 4000K and 25000K daylight. Fig. 13 shows the overall CRIs for all the CdTe PV windows and clear double glazing. It clearly illustrates that all the four types of CdTe PV window are able to achieve the best colour rendering as their Ra are all higher than 95. This is because that the general CRI only accounts for the front eight-test colour samples which are all awarded a high CRI as shown in Fig. 11. The findings suggest that the CIE CRI might not be a comprehensive indication for the colour rendering evaluation as it only considering the colour rendering evaluation for unsaturated colour (i.e. the front eight test colour samples). For the light source such as the daylight transmitted through CdTe PV window, it may have a poor performance on the colour rendering of the saturation colour even though they can have a high performance on the colour rendering of the unsaturated colour.



(a) (b) (c)

Fig. 11 Special CRI of CdTe PV window and clear double glazing (a) 4000K scenarios (b) 6500K scenarios (c) 25000K scenarios.



(a) (b) (c)

Fig. 12. Reference illuminant and test illuminant for CdTe-50% (a) 4000K scenarios (b) 6500K scenarios (c) 25000K scenarios.

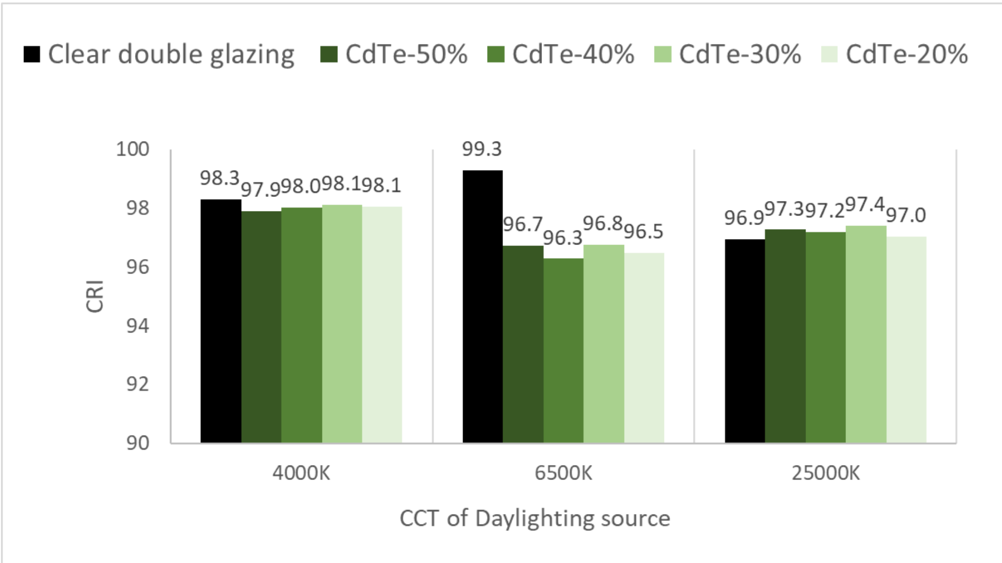


Fig. 13. General CRI of CdTe PV window and clear double glazing.

5. Summary

The overall assessments under all the criteria for CdTe PV windows with different transparency and the reference double-glazing window with 2 WWRs have been shown in Table 2 and 3. All the criteria are classified into four ranks, 'Best', 'Good', 'Reasonable' and 'Unreasonable'. The four ranks for glare, colour appearance and colour rendering have been specified in the section 2 respectively. It is well known that a higher percentage of working hours for UDI $_{100\text{-}2000\ lux}$ or Uo ≥ 0.7 is expected to offer better luminous comfort, however, there are no ranks of the percentage of working hours for these in comparison to other daylight metrics. To match the ranks of glare, colour appearance and colour rendering, the percentages of working hours for UDI $_{100\text{-}2000\ lux}$ and Uo ≥ 0.7 also have also been classified into four ranks. According to Acosta et al. [55], a best design for daylight autonomy requires the percentage of working hours for UDI $_{100\text{-}2000\ lux}$ to be higher than 70%. Therefore, average UDI $_{100\text{-}2000\ lux}$ higher than 70% is classified to be the 'Best'. If the percentage of working hours for average UDI $_{100\text{-}2000\ lux}$ is less than 50%, the period for occupant dissatisfaction with the luminous environment is longer than the period for occupant satisfaction. Therefore, when average UDI $_{100\text{-}2000\ lux}$ is less than 50%, daylight availability for the luminous environment is classified to be 'Unreasonable'. Correspondingly, 60% of working hours are used as the threshold to classify 'Good' and 'Reasonable'. For daylight distribution, similarly, 70%, 60% and 50% of working hours are the thresholds for classifying the 4 ranks of Uo ≥ 0.7. In Tables 2 and 3, dark green block means that the window type in the left column meets the 'Best' rank for the criterion in the top row. Light green block means it meets the 'Good' rank for the criterion. Yellow and red blocks indicate the related window types meet 'Reasonable' or 'Unreasonable' ranks for the criteria respectively. As shown in Tables 2 and 3, all the window types are classified to be 'Best' for both colour appearance and colour rendering criteria. For WWR 60%, CdTe-20% and CdTe-30% demonstrates the best performances as all of the criteria have reached 'Best' or 'Good' ranks, while clear double glazing performs the worst. Although CdTe-40% and CdTe-50% result in the most uniform daylight distribution on the task area, they only achieve 'Reasonable' rank for daylight availability. In addition, CdTe-50% provides 'Unreasonable' rank for glare due to over 16.4% of working hours suffer from intolerable glare with the integration of CdTe-50%. For WWR 30%, as shown in Table 3, CdTe-40% and CdTe-50% have the best performance among all these window types, due to the ranks for all the criteria for CdTe-40% and CdTe-50% are better than or equivalent to 'Reasonable'. Clear double glazing still presents the worst performance. For CdTe-20% and CdTe-30%, they can give rise to the highest daylight availability and also can significantly reduce the risk of glare caused by daylight. However, they result in less uniform daylight distribution on the task area, i.e. Uo> 0.7 reduced from 39% for clear double glazing to approximate 30% for CdTe-20% and CdTe-30%.

Table 2 Rankings of different types of window under all the criterial factors under 60% WWR.

Under 60% WWR	Daylight Quantity	Daylight Quality				Overall ranking
Window type	daylight available	Daylight glare	Daylight distribution	Colour quality (6500K scenarios)		
				Colour appearance	Colour rendering	
Clear double glazing	Average $UDI_{100\text{-}2000\ lux}$ =34%	$DPG_{\leq 0.45}$= 63.1%	$Uo_{\geq 0.7}$ = 69.4%	CCT=6621K	CRI=99.3	5
CdTe-20%	Average $UDI_{100\text{-}2000\ lux}$ =69%	$DPG_{\leq 0.35}$= 98.4%	$Uo_{\geq 0.7}$ = 65.6%	CCT=5295K	CRI=96.7	1
CdTe-30%	Average $UDI_{100\text{-}2000\ lux}$ =64%	$DPG_{< 0.4}$= 93.6%	$Uo_{\geq 0.7}$ = 66.9%	CCT=4955K	CRI=96.3	2
CdTe-40%	Average $UDI_{100\text{-}2000\ lux}$ =59%	$DPG_{< 0.4}$= 92.4%	$Uo_{\geq 0.7}$ = 70.7%	CCT=4847K	CRI=96.8	3
CdTe-50%	Average $UDI_{100\text{-}2000\ lux}$ =50%	$DPG_{\leq 0.45}$= 83.6%	$Uo_{\geq 0.7}$ = 72.6%	CCT=5124K	CRI=96.5	4

* Indications of ranks in the table

Best **Good** **Reasonable** **Unreasonable**

Table 3 Rankings of different types of window under all the criterial factors under 30% WWR.

Under 30% WWR	Daylight Quantity	Daylight Quality				Overall ranking
Window type	daylight available	Glare	distribution	Colour quality (6500K scenarios)		
				Colour appearance	Colour rendering	
Clear double glazing	Average $UDI_{100\text{-}2000\ lux}$ =56%	$DPG_{\leq 0.45}$= 89%	$Uo_{\geq 0.7}$ = 38.7%	CCT=6621K	CRI=99.3	5
CdTe-20%	Average $UDI_{100\text{-}2000\ lux}$ =71%	$DPG_{\leq 0.35}$= 99.5%	$Uo_{\geq 0.7}$ = 28.9%	CCT=5295K	CRI=96.7	3
CdTe-30%	Average $UDI_{100\text{-}2000\ lux}$ =70%	$DPG_{\leq 0.35}$= 97.8%	$Uo_{\geq 0.7}$ = 29.2%	CCT=4955K	CRI=96.3	4
CdTe-40%	Average $UDI_{100\text{-}2000\ lux}$ =68%	$DPG_{\leq 0.35}$= 96.9%	$Uo_{\geq 0.7}$ = 50.1%	CCT=4847K	CRI=96.8	1
CdTe-50%	Average $UDI_{100\text{-}2000\ lux}$ =65%	$DPG_{< 0.4}$= 93.8%	$Uo_{\geq 0.7}$ = 50.9%	CCT=5124K	CRI=96.5	2

* Indications of ranks in the table

Best **Good** **Reasonable** **Unreasonable**

6. Conclusions

PV windows can significantly improve buildings' energy performance compared with the conventional window systems because of its additional power generation advantages. However, its daylighting performance, which can significantly affect occupants' visual comfort, needs to be explored in details. In this study, the daylighting performance in terms of daylight quantity and daylight quality for four types of CdTe PV windows and clear double glazing were investigated. Annual dynamic simulation was used to obtain the indicated metrics (UDI, DGPs, Uo), which were used to evaluate daylight availability, daylight distribution uniformity and daylight glare of applying of CdTe PV windows. CIE standard calculation method was used to calculate CCT and CRI, which are used to quantify the colour quality of applying of CdTe PV windows. The following conclusions can be drawn:

1. UDI indicates that applying CdTe PV window under large WWR (i.e. 60%) can significantly increase the percentage of working hours falling into the useful illuminance ($UDI_{100\text{-}2000lux}$) and desirable illuminance ($UDI_{500\text{-}2000\ lux}$) bins.
2. The presence of all types of CdTe PV windows can reduce the potential of daylight glare.
3. For daylight uniformity evaluation, it was found that CdTe PV windows with high transparencies (i.e. CdTe-40% and CdTe-50%) are more approvable for small WWR.
4. Daylight transmitted through CdTe PV windows has more potential to reduce its CCT to a lower level compared with a clear double glazing.
5. Daylight transmitted through all these four types of CdTe PV windows can result a favourable colour rendering property under three tested daylight scenarios (general CRI of four CdTe PV windows are all higher than 95).

The addressed conclusion in this research would be valuable for building designers and decision-makers to determine the appropriate application of semi-transparent CdTe PV window, and therefore ensure a comfort luminous built environment.

More accurate and advance colour quality metrics such as Colour Quality Scale, Memory Colour Rendering Index, Feeling of Contrast Index, etc. can be applied in future work for light colour quality evaluation for PV windows. Furthermore, a more comprehensive analysis consisting of thermal, daylighting and electrical performance for PV windows needs to be further conducted to provide a better understanding of this application.

Acknowledgments

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