

# 1 **Comprehensive evaluation of windows integrated semi-transparent PV for** 2 **building daylight performance**

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## 8 **Abstract**

9 Building-Integrated Semi-transparent Photovoltaics Window (PV window) has been  
10 considered as one of the potential candidates to replace conventional windows to improve  
11 buildings' energy efficiency hence reducing their carbon emission. With the integration of PV  
12 windows, the indoor luminous-environment may be significantly affected. The presence of  
13 solar cells may cause undesirable shading, low illuminance level and affect colour quality of  
14 the transmitted daylight. Therefore, it is important to comprehensively assess daylight  
15 performance of PV windows to ensure a comfort luminous environment. In this study, the  
16 daylight performance of CdTe PV window with four different transparencies (i.e. 20%, 30%,  
17 40% and 50%) applied to a typical office have been assessed in terms of daylight quantity and  
18 daylight quality. RADIANCE was selected to predict the annual daylight performance through  
19 advanced dynamic metrics including Useful Daylight Illuminance (UDI), Daylight Glare  
20 Probability (DGPs) and Illuminance Uniformity (U<sub>o</sub>). Correlated Colour Temperature (CCT)  
21 and Colour Rendering Index (CRI), which are two attributes to characterise colour quality of  
22 transmitted daylight specified in CIE standard, were used to evaluate performance of the  
23 selected PV windows. CCT and CRI were calculated under three CIE standard daylight  
24 scenarios (CCT of 4000 K, 6500K and 25000K respectively). It is found that CdTe PV window  
25 can significantly improve the homogeneity of daylight distribution on the task area and reduce  
26 risks of daylight glare when compared to these of a conventional double glazing. Moreover,  
27 recommended CCT (i.e. 3300-5000K) can be achieved with the employment of CdTe PV  
28 window under the 4000 K and 6500 K daylight scenarios. All types of CdTe PV windows can  
29 maintain a CRI at a comfortable level i.e. above 90 under the three tested daylight scenarios.

30

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

32

## Nomenclature

$\tau_v$	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 2° Standard Observer
$\lambda$	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

## 2 1. Introduction

3 Building-Integrated Semi-transparent Photovoltaic window (PV window) can be integrated in  
4 the building by replacing conventional glazing system. PV window, which is an innovative and  
5 emerging glazing technology for building application [1] [2] [3], can provide onsite energy  
6 generation and reduce building energy consumption to potentially regulate CO<sub>2</sub> emission [4].  
7 When integrating different types of solar cells (e.g. amorphous silicon (a-Si) solar cells,  
8 Cadmium telluride (CdTe) thin film solar cells, Dye-sensitized solar cells etc.) into glazing unit  
9 to compose a semi-transparent PV window, the presence of solar cells and the solar cell  
10 covering ratio may significantly affect PV window electricity generation rate, indoor thermal  
11 environment, luminous environment and building energy performance. When solar radiation  
12 incidents on the surface of a semi-transparent PV window, part of the solar radiation is captured  
13 by these solar cells to generate electrical power, while part of the solar radiation penetrates into  
14 the indoor space through gaps between solar cells, allowing for passive heating and satisfaction  
15 of daylight needs. Increasing transparency (i.e. reducing solar cell covering ratio) of a semi-  
16 transparent PV window leads to a reduction of electrical generation, but more daylight is  
17 permitted to transmit through contributing to the indoor luminous environment. Zhang and Lu  
18 [5] have investigated the electrical and daylighting performance of three amorphous silicon (a-

1 Si) based semi-transparent PV window with different transparency (i.e. 10%, 16% and 26%)  
2 through numerical simulation. Results indicated that with the transparency of PV window  
3 increasing from 10% to 26%, the daylighting performance was significantly improved, while  
4 the annual electrical generation of PV window gradually reduced from 173 kWh to 132 kWh  
5 in Shanghai, China. Barman et al. [6] explored the energy performance of a one-floor building  
6 integrated with five types of CdTe PV windows with different transparency (i.e. from 6% to  
7 27.5%) in Jaipur, India. Simulation results showed that the energy generation of CdTe PV  
8 window decreases with the increase of its transparency. Applying CdTe PV window with lowest  
9 and highest transparency (i.e. 6% and 27.5%) in the south orientation generated electricity of  
10 119.6 and 74.74 kWh/m<sup>2</sup>-year respectively. At the meantime, building energy consumption  
11 increases with the increasing of CdTe PV window transparency. The increment is mainly  
12 resulted by the dropping in energy generation and a slight increasing in cooling energy demand.  
13 Miyazaki et al. [7] have investigated the effect of a-Si PV windows with different transparency  
14 (i.e. from 10% to 80%) on building energy performance of an office located at Tokyo, Japan. It  
15 was found that although a-Si PV window with the lowest transparency (i.e. 10%) always  
16 generates the maximum amount of electricity. However, due to the energy consumption for  
17 artificial lighting is larger for the a-Si PV window with low transparency, the best building  
18 energy performance for the office is achieved when it is integrated with a-Si PV window with  
19 80% transparency for WWR of 30%. The presence of solar cells also significantly affect the  
20 optical properties (e.g. spectral transmittance, light-scattering characteristics, etc.) of the  
21 window unit, resulting a distinct daylighting environment in a space served by them when  
22 compared with that of a normal double glazing. Therefore, in seeking to ensure a comfort  
23 luminous environment, evaluation of the daylighting performance of applying PV windows to  
24 buildings is increasingly required. The daylighting performance can be explored through two  
25 aspects via daylight quantity and daylight quality. For daylight quantity assessment, the metric  
26 of Daylight Factor (DF) is frequently formalised within national standards and widely  
27 employed by architects and designers [8-10]. This metric describes the ratio of internal  
28 illumination at a given point to external horizontal illumination [11]. The traditional method of  
29 acquiring DF is restricted to calculations based on an unobstructed CIE overcast sky. The recent  
30 development of this approach enables it to become applicable for 15 CIE standard skies[12]  
31 and takes into account building directions, solar positions and the effect of direct and reflected  
32 sunlight [13]. Once annual climate data is available for a selected location, climate-based  
33 metrics, such as Useful Daylight Illuminance (UDI) [14] and Daylight Autonomy (DA) [15],  
34 are able to provide more comprehensive, accurate and dynamic predictions of daylight

1 availability while representing time varying daylight illuminance. It has seen an increasing  
2 number of studies that using this kind of climate-based dynamic metrics to investigate the  
3 daylight quantity of applying window integrated with PV modules in the literature [16-18].  
4 Kapsis et al. [19] have investigated the potential impact of a semi-transparent photovoltaic  
5 module on the daylighting performance of an office building via dynamic simulation method.  
6 Annual spatial Daylight Autonomy, which was calculated based on simulation results, indicated  
7 that sufficient daylight for the office can be provided by the presence of semi-transparent  
8 photovoltaic module with 30% visible transmittance. Sun et al. [20] explored the dynamic  
9 daylighting performance of a cellular office of applying a CdTe PV window with the adoption  
10 of different window design scenarios under different climates (i.e. Harbin and Guangzhou)  
11 using RADIANCE. The UDI calculated based on simulation results indicated that designs with  
12 a large portion of the window area covered by PV window while keeping sufficient daylighting  
13 area provided the optimum daylight availability under the climate of Guangzhou, while  
14 covering the whole window area by PV window provided the optimum daylight availability  
15 under the climate of Harbin.

16 Daylight quantity is not the only factor that affects luminous environment of an indoor space.  
17 Velasco [21] states that glare, incorrect distribution of light density, low light colour quality may  
18 also exist as potential risks that can negatively affect human visual comfort in terms of human  
19 health, mood, activity and work efficiency [22]. These factors (e.g. glare, daylight distribution  
20 and daylight colour quality) determine indoor daylight quality. Glare is a crucial criteria in the  
21 occupant visual comfort evaluation, which describes the situation where the luminance fall in  
22 the field of view is more than the brightness to which eyes are adapted. Glare shall be limited  
23 as the appearance of glare can result in errors, fatigue and accidents. The daylight glare metric  
24 named Daylight Glare Probability (DGP), which was introduced by Wienold and Christofferen  
25 [23] in 2006, has become the preferred metric for assessing glare for the luminous environment  
26 in many research [24-26]. Glare has been considered in a number of visual comfort evaluations  
27 for building integrated with PV window. Cannavale [27] carried out the daylight glare  
28 evaluation for a hypothetical test-room that equipped with PV window, commercial solar  
29 control glass and a clear glass through simulation. It was found that the occurrence of high DGP  
30 can be significantly reduced by PV window which was outperformed both solar control glass  
31 and clear glass. The daylight spatial distribution is another factor considered in the daylight  
32 quality evaluation. Uniform daylight spatial distributions will promise occupants to perceive  
33 the luminous environment continuously and without sudden breaks caused by illuminance level  
34 drops. Uniformity metrics include illuminance uniformity ratio (UR) defined by standard IBSE

1 guide A [28] and illuminance uniformity ( $U_0$ ) specified by BS EN 12464 [29]. They have been  
2 applied in the research of daylight uniformity exploration [30, 31]. Zomorodian [32] have  
3 carried out the dynamic simulation for the evaluation of daylight distribution for applying  
4 window with different configuration. The result was analysed by  $U_0$ , which indicated that  
5 lighting uniformity would reduce with the increasing of window-head-height and decreasing of  
6 windowsill. Other than daylight glare and distribution uniformity, colour quality of the  
7 transmitted daylight is equally important when assessing the indoor luminous environment.  
8 This will affect the colour appearance of a space which will contribute to the psychological and  
9 physical well-being of the occupants. CIE BS EN 12464-1 [29] recommended two metrics to  
10 characterize the colour qualities of a light source (i.e. both artificial light source and daylight  
11 transmitted through windows). They are Correlated Colour Temperature (CCT) and Colour  
12 Rendering Index (CRI) [33]. These two metrics have a few implementations for evaluating the  
13 colour quality of daylight modified by different PV windows [34-36]. Nandar et al. [37]  
14 investigated the colour quality of the daylight passing through different types of semi-  
15 transparent photovoltaic (i.e. with 20%, 30%, 40% and 50% transparency respectively) by  
16 analysing CCT and CRI based on measured spectral transmittance of the selected PVs. It is  
17 shown that the modules in neutral a-Si-colour presents excellent colour rendering, but the  
18 modules in red and blue colour shown a weak colour rendering capacity with CRI less than 90.  
19 Ghosh et al. [38] evaluated the colour quality of the light transmitted through multi-crystalline  
20 based semi-transparent Photovoltaic-vacuum glazing. They found that the semi-transparent PV-  
21 vacuum glazing with transparency 35% and 42% offered higher allowable CCT and CRI than  
22 those of 30% and 40% transparent states of suspended particle device glazing, respectively.  
23 Although, in the literature, efforts have been made to evaluate daylight performance of applying  
24 PV windows for each individual aspects (i.e. daylight availability, glare, daylight distribution  
25 and colour quality), to the best of the authors' knowledge, systematic and holistic investigations  
26 accounting all the aspects that may affect the luminous environment has not been seen. In  
27 practice, this information can be used by construction professionals to ensure that PV windows  
28 are designed appropriately and applied correctly. Thus, a comprehensive daylight performance  
29 evaluation in terms of daylight quantity (i.e. daylight availability) and daylight quantity (i.e.  
30 glare, daylight distribution and colour quality) for the building integrated PV window is  
31 necessarily needed.

32 This paper provides a comprehensive assessment on daylight performance when applying semi-  
33 transparent PV windows to buildings through a holistic consideration of daylight quantity and  
34 daylight quality. Window integrated thin film CdTe solar cells with four transparency were

1 investigated to understand the influence of their transparency on the overall daylight  
2 performance. RADIANCE are used to predict the dynamic daylight availability, uniformity and  
3 glare probability of applying these four CdTe PV windows to an office with different window  
4 to wall ratio under a climate of Birmingham, UK. Useful Daylight illuminance (UDI) is used  
5 as the metric to evaluate daylight quantity while metrics of Illuminance Uniformity ( $U_O$ ) and  
6 Daylight Glare Possibility (DGP) are used to assess daylight quality in terms of homogeneity  
7 of daylight distribution and glare. The measured spectral properties of these four CdTe PV  
8 windows are used to calculate the colour quality of the transmitted light under three different  
9 daylight scenarios. Metrics of Correlated Colour Temperature (CCT) and Colour Rendering  
10 Index (CRI) are then used to quantify their colour quality.

11

## 12 **2. Daylight performance assessment metrics**

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

17

### 18• Useful Daylight illuminance (UDI)

19 UDI, which is developed by Nabil and Mardaljevic [14], is widely used by a number of  
20 researchers for accounting climate-based analyses of daylight availability [39, 40]. It is different  
21 from conventional static metrics (e.g. daylight factor), which only result a single value under a  
22 specific condition. UDI describes the illuminance level on each point considered for each  
23 daylight hour through a course of a year. This is calculated by dividing hourly illuminance into  
24 three bins within a year. The three bins include the undersupply bin ( $UDI_{100 \text{ lux}}$ , where  
25 illuminance  $< 100 \text{ lux}$ ), useful illuminance bin ( $UDI_{100-2000 \text{ lux}}$ , where  $100 \text{ lux} \leq \text{illuminance} \leq$   
26  $2000 \text{ lux}$ ) and oversupply bin ( $UDI_{2000 \text{ lux}}$ , where illuminance  $> 2000 \text{ lux}$ ). Considering the  
27 most desirable illuminance range for a typical office is  $500 \text{ lux}-2000 \text{ lux}$  [41], the useful  
28 illuminance bin ( $UDI_{100-2000 \text{ lux}}$ ) can be further subdivided at a threshold of  $500 \text{ lux}$ . The most  
29 desirable bin ( $UDI_{500-2000 \text{ lux}}$ ) means the daylight illuminance is sufficient as the sole source of  
30 illumination [42].

31

### 32• Daylight illuminance uniformity ( $U_O$ )

1 The homogeneity of indoor daylight distribution can be evaluated by  $U_0$ , which is obtained  
2 using the minimum illuminance divided by the average illuminance. In this research, the  
3 minimum  $U_0$  on the task area within a cellular office was investigated. According to BS EN  
4 12464 [29], if the office is used for filing, copying, etc., the minimum  $U_0$  on the task area  
5 should be higher than 0.4. If it is used for writing, typing, reading or data processing, the  
6 recommended minimum  $U_0$  on the task area is 0.6. If it is used for technical drawing, the  
7 required minimum  $U_0$  on the task area is 0.7. According to the recommended minimum value,  
8  $U_0$  is divided into four acceptance bins which are  $U_0 \geq 0.4$ ,  $0.4 < U_0 < 0.6$ ,  $0.6 > U_0 > 0.7$  and  
9  $U_0 \geq 0.7$ .

#### 10• Simplified Daylight Glare Probability (DGPs)

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

25

#### 26• Correlated Colour Temperature (CCT)

27 Colour appearance of a light source can be quantified by correlated colour temperature (CCT).  
28 CCT, which is usually given in degrees Kelvin (K), is a one-dimensional description of the  
29 colour of near-white light sources. Defining the colour appearance of a light source using the  
30 temperature on the blackbody locus that most closely resembles the light source's chromaticity  
31 coordinates in the CIE chromaticity diagram is named as Correlated Colour Temperature (CCT)  
32 [44]. A low CCT indicates the light is reddish, a high CCT is bluish-white and the light with  
33 the middle range of CCT will present neutral colour. It has been recommended that a preferred

1 transmitted daylight should have CCT within the range between 3000K-7500K [35]. It means  
 2 if CCT of transmitted daylight falling in this range, colour appearance of the transmitted  
 3 daylight is classified to the best.

4  
 5• Colour Rendering Index (CRI)

6 CRI can be used to characterize colour rendering properties of the transmitted light. This  
 7 describes how well the transmitted light renders a set of colour samples relative to their  
 8 rendering under a reference illuminant. 14 test colour samples are specified by CIE 1995 [45]  
 9 for colour rendering evaluation as shown in Table 1. The front eight test colour samples cover  
 10 the hue circle, are moderate in saturation and have similar lightness [46]. The rest six test colour  
 11 samples contain the saturated red, yellow, green and blue, and complexion and foliage colours.  
 12 The colour rendering capacity of light source for each test colour sample can be evaluated by  
 13 specific CRI (Ri). The average of the special CRIs for the front eight test colour samples is  
 14 defined as general CRI (Ra). ). It has been recommended by BS EN 1246-1 [29] that the  
 15 minimum acceptable Ra is 80. Ra higher than 90 is considered as a good indication of colour  
 16 rendering for luminous environment [37], while Ra higher than 95 is considered as a best colour  
 17 rendering indication [47]. Accordingly, colour rendering of light is classified into four ranks.  
 18 They are ‘Best’ (where  $Ra \geq 95$ ), ‘Good’ (where  $95 > Ra > 90$ ), ‘Reasonable’ (where  $90 > Ra >$   
 19  $80$ ) 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		

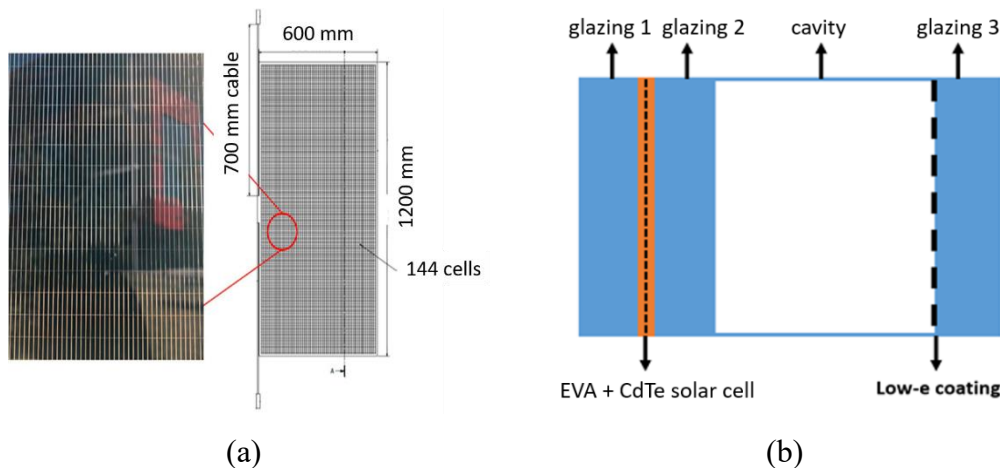
20 Table 1 CIE test colour samples.

21



1 **3. Research methodology**

2 The daylight quantity and daylight quality of CdTe PV window have been comprehensively  
3 investigated using an incorporative method including numerical simulation (RADIANCE) and  
4 experimental test to explore its implementation. The tested windows with integrated CdTe solar  
5 cell includes four types: CdTe-20%, CdTe-30%, CdTe-40% and CdTe-50%. Each percentage  
6 indicates the proportion of transparent area (i.e. area that not covered by solar cells) over the  
7 overall glazing area. The CdTe PV window sample is shown in Fig.1. (a) [20], it can be seen  
8 that CdTe solar cells are opaque and spaced properly in order to attain the required level of  
9 transparency and outdoor views. The configuration of a typical CdTe PV window is shown in  
10 Fig. 1 (b). The properly placed CdTe solar cells are encapsulated between ethylene vinyl acetate  
11 (EVA) films and sandwiched between two clear glazing panes (glazing 1 and glazing 2 in Fig.  
12 1 (b)). The other layer is a low-e coated glazing pane (glazing 3 in Fig. 1 (b)). The cavity  
13 between glazing 2 and glazing 3 is 20mm and filled with Argon. A normal clear glazing was  
14 also tested as a reference window for comparison.



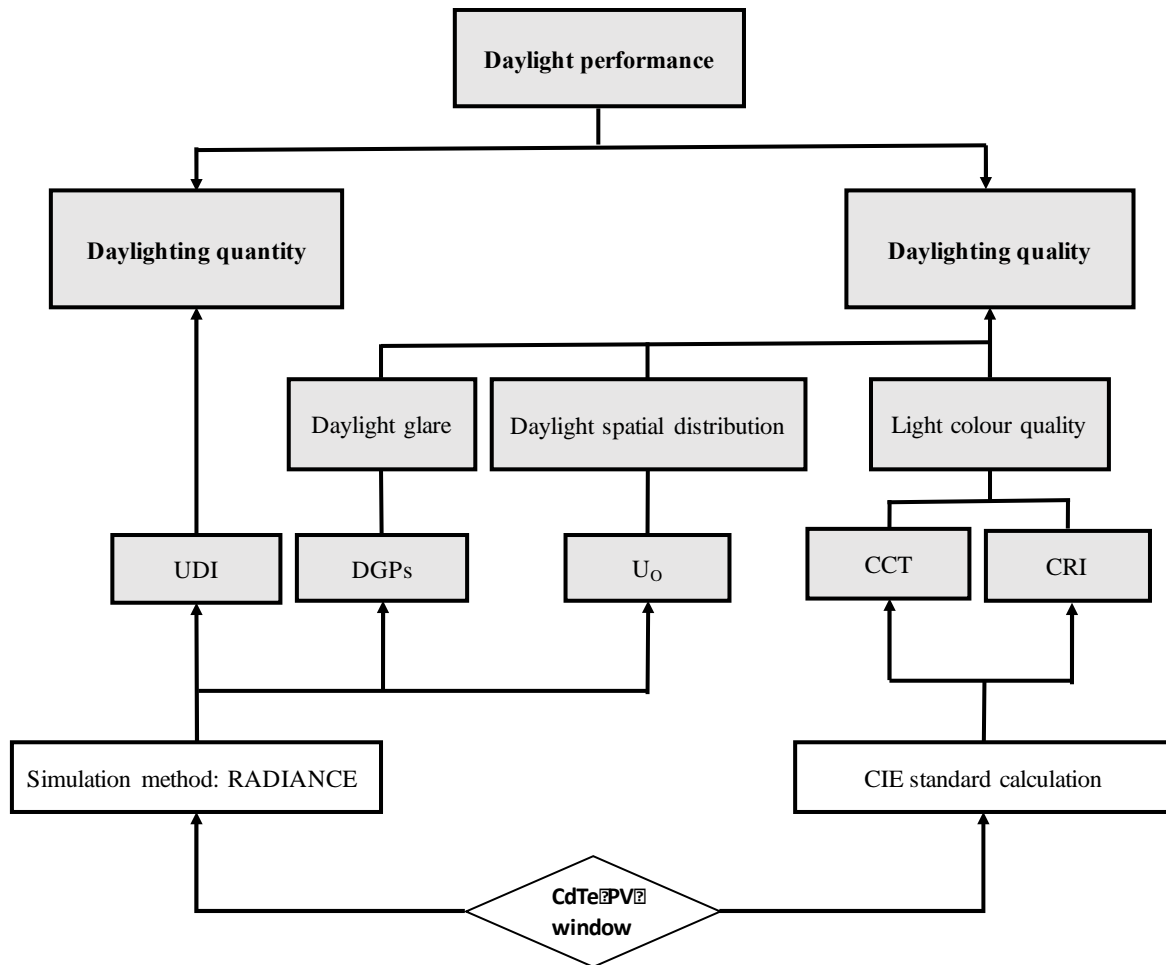
15  
16  
17 Fig.1. (a) CdTe PV window sample (b) Configuration of CdTe PV window.  
18

19 *3.1. Overview of the analysis method*

20 The comprehensive evaluations of building daylight performance for CdTe PV windows were  
21 based on attaining a balance between daylight quantity and daylight quality. As shown in Fig.  
22 2, daylight quantity evaluation was analysed using dynamic metric, UDI. Daylight quality  
23 evaluation was carried out in terms of daylight glare, daylight spatial distribution and light  
24 colour quality. Daylight glare was assessed by DGPs and daylight spatial distribution was  
25 indicated by  $U_0$ . The dynamic metrics UDI, DGPs and  $U_0$  were determined based on the hourly  
26 daylight illuminance predicted by RADIANCE simulation. The colour quality can be assessed  
27 by metrics of CCT and CRI. These can be acquired through CIE standard calculation which

1 was carried out based on the measured spectral transmittance of CdTe PV windows. Detailed  
 2 information of the research methodologies can be found in next sections.

3



4 Fig. 2 Flowchart of modelling and calculating daylighting performance for CdTe PV window.

5 In this Fig., white rectangles indicate the daylight performance processing methods. Grey  
 6 rectangles represent the expected daylight performance metrics' values from the related  
 7 processes.

8

9  
 10 *3.2. Simulation methods for UDI, DGPs and U<sub>o</sub> acquiring*

11 The three daylight performance metrics UDI, DGPs and U<sub>o</sub> were obtained based on annual  
 12 hourly simulation results from RADIANCE which is a research-grade simulation tool and has  
 13 been validated by several studies [48-50]. Due to the configuration of the CdTe PV window,  
 14 multiple inter-reflection will occur when daylight passes through it. For describing such a  
 15 window system in RADIANCE, the complex interactions within the CdTe PV window were  
 16 substituted by a pre-calculated transmission matrix (T). The light passing from sky to the

1 external surface of the window and the light passing from interior surface to the viewpoint were  
2 described by the daylight matrix (D) and view matrix (V) respectively. As the office  
3 information, including the surrounding environment, orientation, office geometry, furniture and  
4 all the surface properties, was input, the daylight matrix (D) and view matrix (V) can be  
5 generated. The combination of the three matrices (T, D and V) used to describe light path is  
6 called "Three-phase method", which was employed in this research to carry out the annual  
7 daylighting simulation for CdTe PV window. The corresponding equations are given as follow:

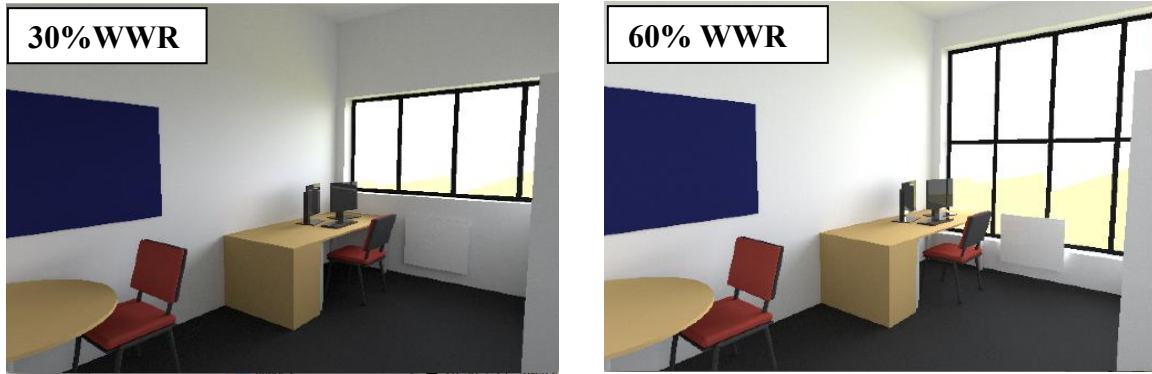
$$8 \quad i = VDT s \quad (1)$$

$$9 \quad I = VDTS \quad (2)$$

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

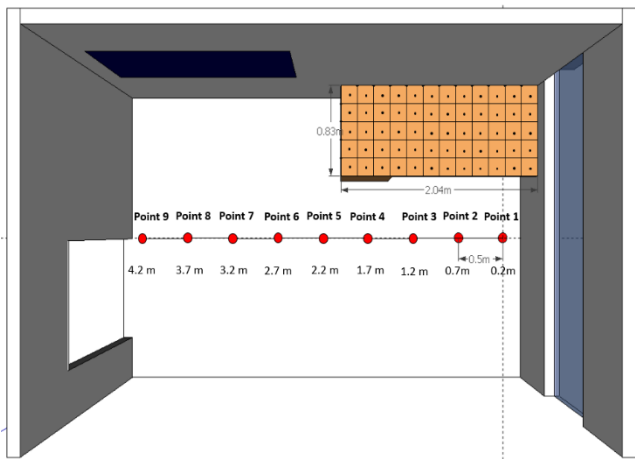
19 The simulation model is a south-faced cellular office with dimensions of 2.9 m (width)  $\times$  4.4  
20 m (depth)  $\times$  3.3 m (height). In this research, 60% WWR and 30% WWR were selected to  
21 investigate the daylight performance of the CdTe PV window, while the corresponding window  
22 dimension is 1.3 m (height)  $\times$  2.65 m (width) and 2.6 m (height)  $\times$  2.65 m (width) respectively,  
23 as shown in the renderings Fig. 3 (a) and (b). Visible reflectance of the purely diffused office  
24 surfaces were 30% (floor), 80% (walls) and 80% (ceiling) respectively. It was assumed that  
25 there are no any obstructions outside the office, such as surrounding buildings and vegetation.  
26 For the daylight quantity evaluation, nine calculated points on office working plane (with 0.75  
27 m height) were set along the central line of the office from window to the end wall. The distance  
28 between each calculated point is 0.5m, while the first point is 0.2 m away from the window  
29 position in the horizontal direction as shown in Fig. 3 (c) (indicated by red points). The surface  
30 of the desk with dimensions of 0.83 m (width)  $\times$  2.04 m (length) was determined as the task  
31 area for the uniformity evaluation. An illuminance grid on the task area was determined to  
32 indicate the points at which the illuminance value was calculated for  $U_0$  evaluation as shown  
33 in Fig. 3 (c). The dimension of grid cells, which is 0.166m  $\times$  0.17 m, satisfied the requirement

1 of BS EN 12464 [29] on the aspect ratio of the grid cell.-The office is designed for the people  
 2 who positioned near the window. Therefore, the glare evaluation is carried out with considering  
 3 that the location of the view point is 1.2m away from the window and 1.2 m above the floor on  
 4 the centre axis of the room while the observer facing the desk as indicated in Fig. 3 (d). A  
 5 validated RADIANCE model has been used for this work [40].

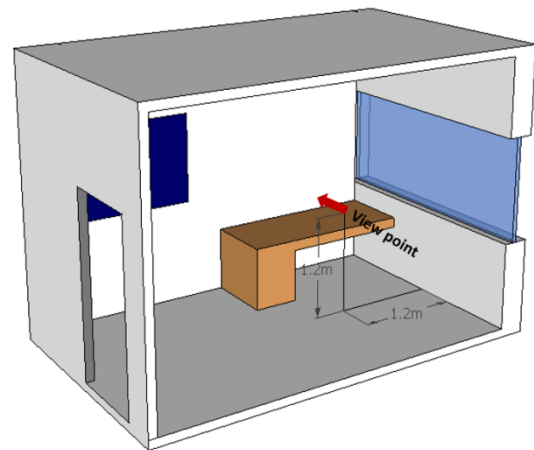


6 (a)

7 (b)



8 (c)



9 (d)

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

13 *3.3. Experimental measurement and calculation process for CCT and CRI acquiring*

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

1

2 3.3.1. Spectral transmittance measurement

3

4 The spectral transmittances for CdTe windows and clear double glazing over the wavelength

5 range of 380-780 nm were tested using the instrument demonstrated in Fig. 4. OceanOptics

6 HL2000 light was used as the light source. The light source perpendicularly transmitted

7 through the tested PV window, which is fixed closely on the port of a transmittance integrating

8 sphere (FOIS-1). All the transmitted lighting in the forwards direction has been collected by

9 the integrating sphere. The spectrometer (OceanOptics VIS-NIR-ES spectrometer) used to

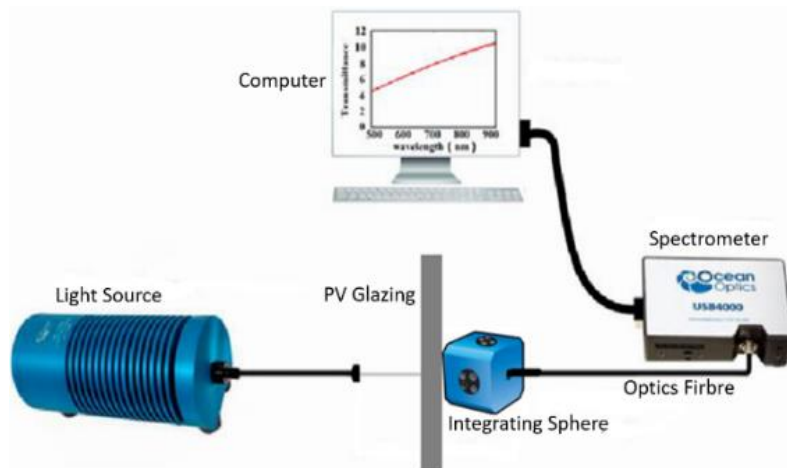
10 measure the spectral transmittance of the collected light, while the measurement results are

11 shown in Fig.5. The clear double glazing has a low transmittance in wavelength range of

12 600nm-700nm, while has a relative high transmittance in the wavelength range of 400nm-

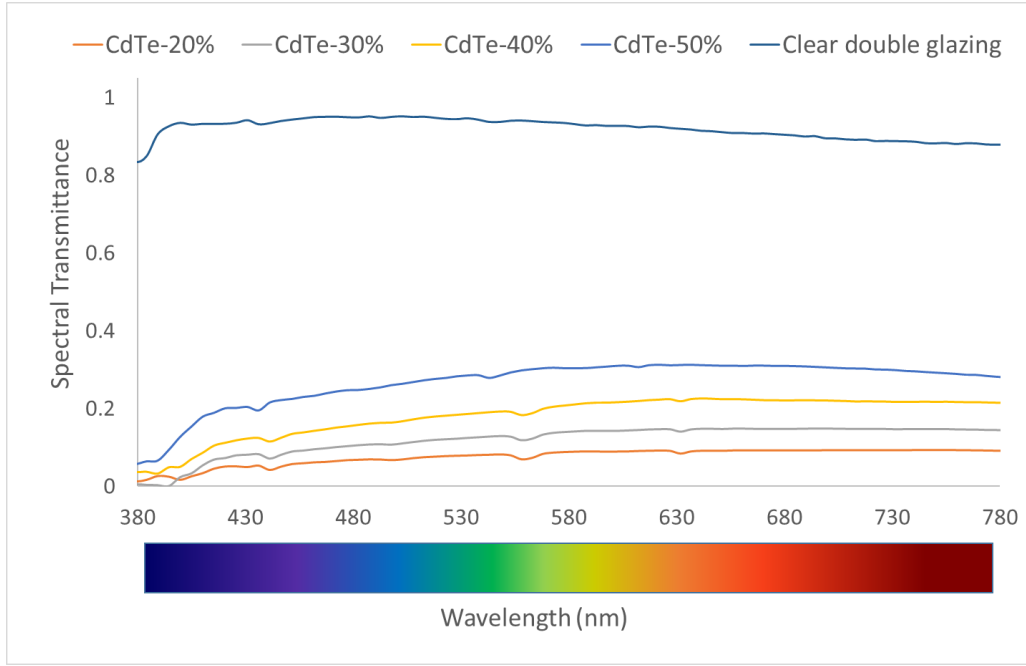
13 500nm. Differ from clear double glazing, CdTe PV windows show relative high spectral

14 transmittance in the wavelength range of 600nm-700nm.



15

16 Fig.4. CdTe PV window spectral transmittance measurement.



1  
2 Fig.5 Spectral transmittance of CdTe PV windows and clear double glazing

3

### 4 3.3.2. Calculation process

5

6 Three CIE standard daylight illuminants with CCT of 4000K, 6500 K and 25000K,  
7 representing three different daylight scenarios, are commonly used to embody weak daylight  
8 in the early morning, normal overcast daylight and extreme summer daylight respectively [51]  
9 [52]. They were selected in this study to evaluate the CCT and CRI for these CdTe PV windows.

10 The acquirement process of CCT for daylight transmitted through each CdTe PV window is  
11 given in equation (3-9) [53]:

$$X_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\tau(\lambda)\bar{x}(\lambda)\Delta\lambda \quad (3)$$

$$Y_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\tau(\lambda)\bar{y}(\lambda)\Delta\lambda \quad (4)$$

$$Z_i = \sum_{\lambda=380nm}^{780nm} SPD(\lambda)\tau(\lambda)\bar{z}(\lambda) \quad (5)$$

$$x = \frac{X}{X + Y + Z} \quad (6)$$

$$y = \frac{Y}{X + Y + Z} \quad (7)$$

$$n = \frac{x - 0.3320}{0.1858 - y} \quad (8)$$

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \quad (9)$$

1 where, X, Y and Z are the tristimulus values that used to describe the colour of the transmitted  
 2 light based on human visual reaction, which are defined in the CIE 1931 chromaticity diagram.  
 3  $SPD(\lambda)$  is the spectral power distribution (SPD) of the three CIE standard daylight scenarios  
 4 (i.e. daylight illuminants with CCT of 4000K, 6500K and 25000K).  $\tau(\lambda)$  is the spectral  
 5 transmittance of the four types of CdTe PV window.  $\bar{x}\bar{y}\bar{z}$  are the CIE standard colour-matching  
 6 functions for the CIE 1931 2° Standard Observer.  $\Delta\lambda$  is the wavelength interval.  
 7 For calculating CRI, CIE 1931 tristimulus values (XYZ) of reference illuminant and test  
 8 illuminant that reflected by tested colour samples were determined firstly. XYZ of each group  
 9 was transformed into 1964 colour space  $W^*, U^*, V^*$  by considering chromatically adaptation  
 10 transform. The resultant colour shift ( $\Delta E_i$ ) is determined by calculating the colour difference  
 11 between the eight-tested colour samples that illuminated under reference illuminant and that  
 12 under test illuminant. Specific colour rendering index ( $R_i$ ) is calculated for these tested colour  
 13 samples based on the  $\Delta E_i$  of each colour respectively.  $R_a$  is the arithmetical mean of the eight  
 14 colour samples. Those are derived by equation (10-15):

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

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

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

$$\Delta E_i = [(U_{r,i}^* - U_{t,i}^*)^2 + (V_{r,i}^* - V_{t,i}^*)^2 + (W_{r,i}^* - W_{t,i}^*)^2]^{1/2} \quad (13)$$

$$R_i = 100 - 4.6\Delta E_i \quad (14)$$

$$R_a = 1/8 \sum_{i=1}^8 R_i \quad (15)$$

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

19

## 20 **4. Result and discussion**

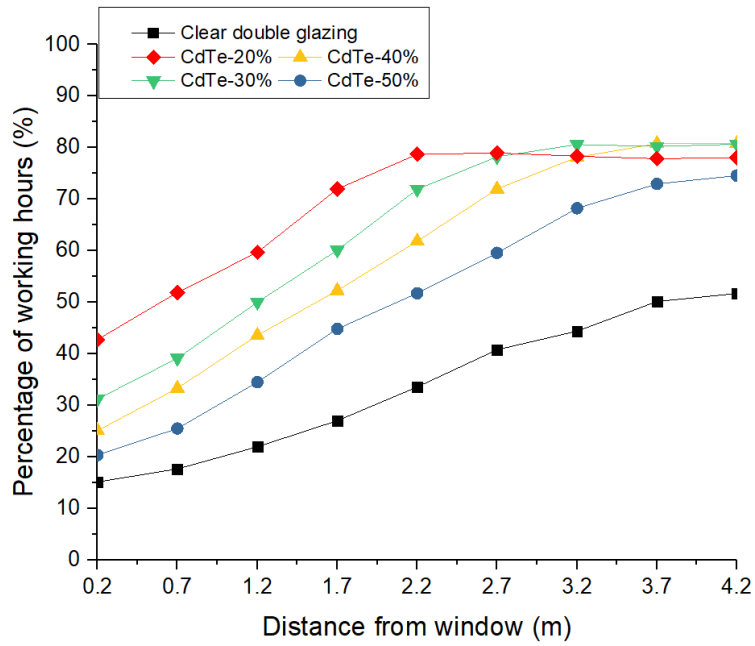
### 21 *4.1. Daylight quantity: Useful Daylight Illuminance (UDI) for CdTe PV window*

22

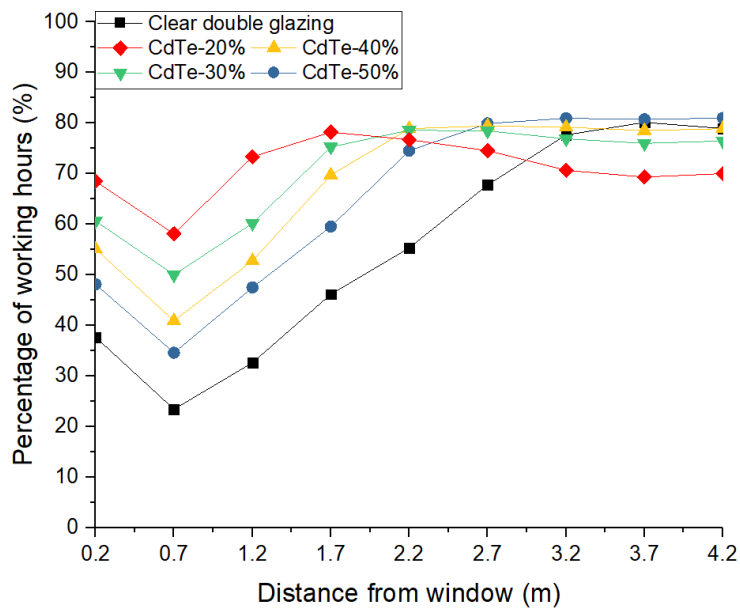
23 Two range of useful illuminance bin range from 100 to 2000lux (wide range) and 500 to  
 24 2000lux (comfortable range) were studied. The obtained UDIs for working hours from 8:00 to

1 17:00 for the central line from the window to the end wall for the cellular office are illustrated  
2 in Figs. 6 and 7, respectively. Fig 6 (a) and (b) shows UDI in a wider useful illuminance bin  
3 range from 100 to 2000lux with 60% and 30% WWR, respectively. From Fig 6 (a), it can be  
4 seen that when WWR is 60%, significant improvement over clear double glazing is achieved  
5 by the presence of semi-transparent CdTe PV windows. For example, useful illuminance is in  
6 the range from 15% to 52% for double glazed window and 20% to 75% for CdTe-50% along  
7 the central line from the window to the end wall. CdTe-20% delivers the best daylighting  
8 performance, it has a  $UDI_{100-2000lux}$  in the range from approximately 43 to 78%. For CdTe-30%  
9 and CdTe-40%, percentage of working hours for illuminance falling in the range of 100-2000  
10 lux is 31%-81% and 25%-81% respectively. Both of them are better than that of CdTe-50%,  
11 but less than CdTe-20%. The  $UDI_{100-2000 lux}$  for all window with 30% WWR are shown in Fig.  
12 6 (b). It can be seen that the CdTe PV windows can improve the  $UDI_{100-2000 lux}$  when compared  
13 with that of the clear double glazing in the range from the window to a distance of 2.7m away  
14 from it. However, there is no significant improvement for the CdTe windows in a distance  
15 above 2.7m away from the window, especially for CdTe-20%, CdTe-30% and CdTe-40%.  
16 Considering the most desirable illuminance range for a typical office is 500 lux-2000 lux [41],  
17 the most desirable bin in the range from 500 to 2000 lux ( $UDI_{500-2000 lux}$ ) was further analyzed  
18 for CdTe PV window shown in Fig. 7. From Fig. 7(a) it can be seen that with a 60% WWR,  
19 CdTe PV windows other than CdTe-20% can provide an improved daylight performance when  
20 replacing the clear double glazing. However, when WWR is reduced from 60% to 30% as  
21 shown in Fig. 7 (b), the daylight performance of CdTe PV windows become undesirable, while  
22 significant reduction of desirable daylight in the region of the room close to the end wall can  
23 be observed. For example, the percentage of working hours in  $UDI_{500-2000 lux}$  for CdTe-20% is  
24 over 10% to 50% lower than that of clear double glazing at the distance from 2.2 m to the end  
25 wall. It can also be seen that the  $UDI_{500-2000 lux}$  is at least approximately 10% lower than the  
26  $UDI_{100 to 2000 lux}$ . This might be explained that there are more hours of the illuminance within  
27 the range from 100 to 500 lux.  
28





(a)

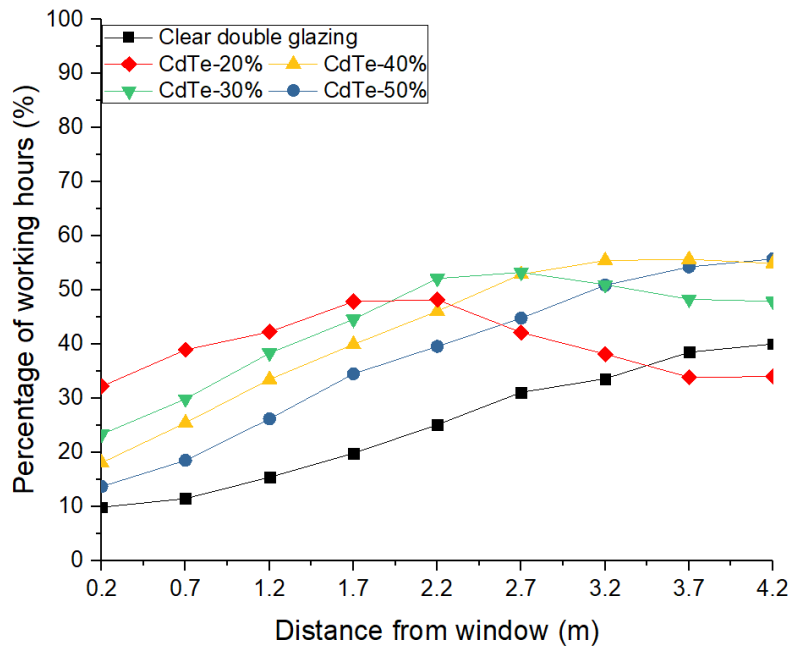


(b)

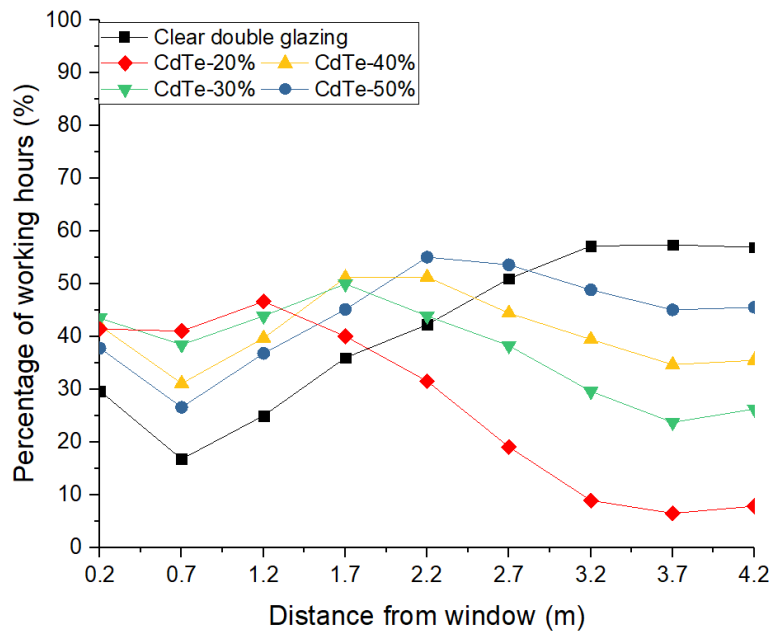
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5 **Fig. 6.** UDI<sub>100-2000lux</sub> bin at points along the central line from window to end wall with the four  
6 types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR  
7 (b) 30% WWR.



(a)



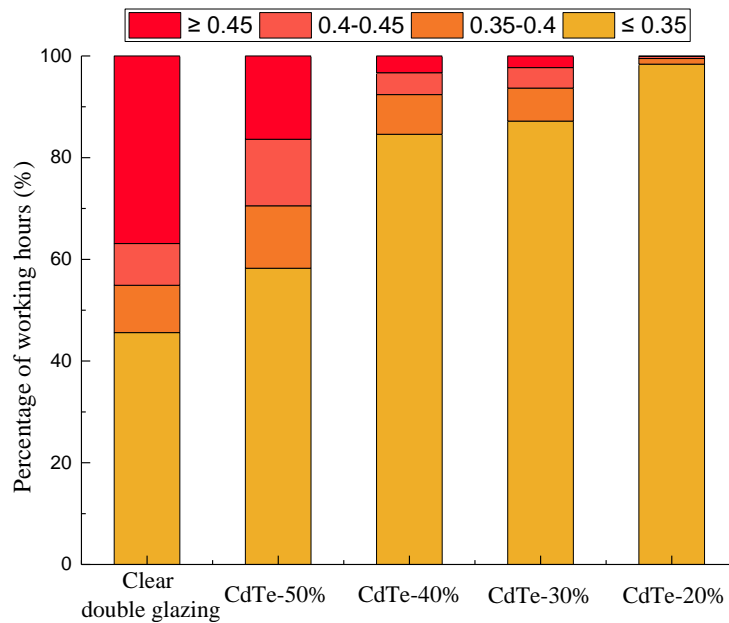
(b)

**Fig. 7.** UDI<sub>500-2000lux</sub> 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

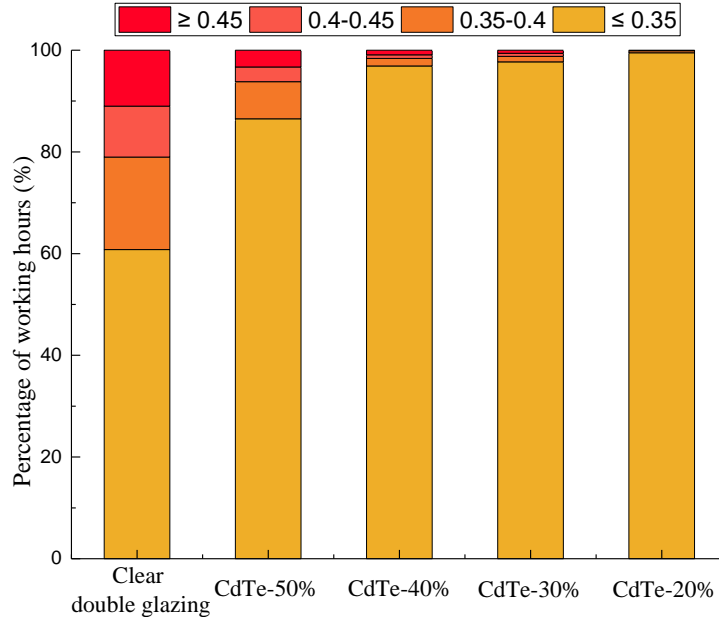
##### 4.2.1. Daylight glare: simplified daylight glare probability (DGPs) for CdTe PV window

1 The obtained DGPs for the selected semi-transparent CdTe PV windows and the clear double  
 2 glazing under WWR of 60% and 30% are shown in Fig. 8. DGPs is calculated by assuming the  
 3 occupant position which is 1.2m away from the window at a 1.2 m height. When replacing the  
 4 clear double glazing window with the CdTe PV window, the DPG can be significantly  
 5 improved. For WWR of 60%, as shown in Fig. 8 (a), it can be seen that when CdTe-20% is  
 6 applied, the acceptance of glare has 'Best' classification, as imperceptible glare (i.e.  $DPG \leq$   
 7  $0.35$ ) is over 95% of working hours. CdTe-30% and CdTe-40% offer 'Good' classification, the  
 8 period for perceptible glare (i.e.  $DPG < 0.4$ ) is over 95% of working hours. CdTe-50% and  
 9 clear double glazing however, are classified to be 'Unreasonable', as intolerable glare (DGPs  
 10  $\geq 0.45$ ) is over 5% of working hours. Under the 30% WWR as shown in Fig. 8 (b), CdTe-20%,  
 11 CdTe-30% and CdTe-40% PV windows provide the 'Best' classification and CdTe-50% offers  
 12 the 'Good' classification for the acceptance of glare. When clear double glazing is applied, the  
 13 acceptance of glare is classified to be 'Unreasonable'.



(a)

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 15  
 16

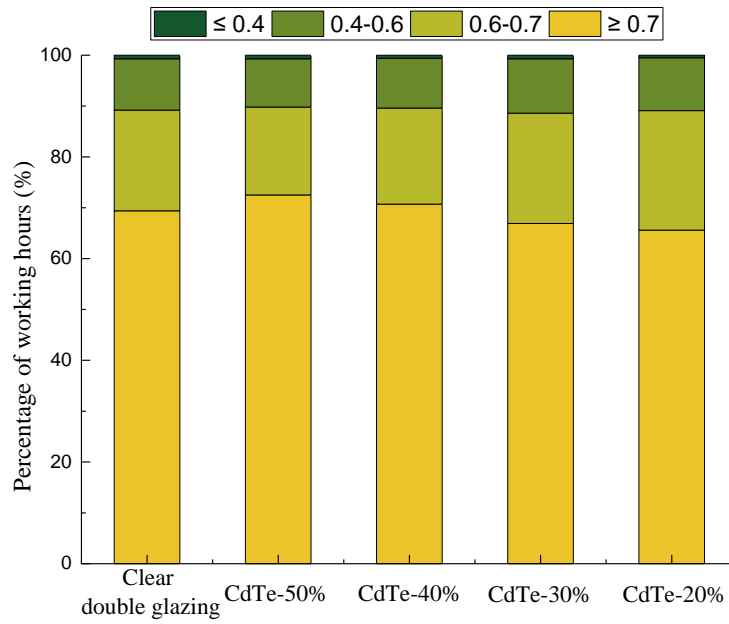


(b)

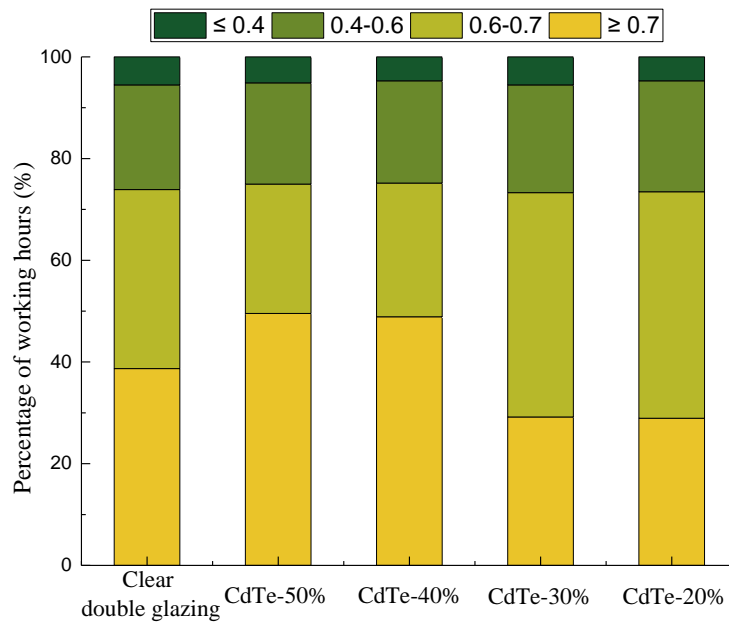
Fig. 8. DGPs of the four types of CdTe PV window and clear double glazing under two different WWR. (a) 60% WWR (b) 30% WWR

#### 4.2.2. Daylight distribution: Illuminance uniformity ( $U_0$ ) for CdTe PV window

Annual predictions of the  $U_0$  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  $U_0$  in the range  $\geq 0.7$  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,  $U_0$  in the range  $\geq 0.7$  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)



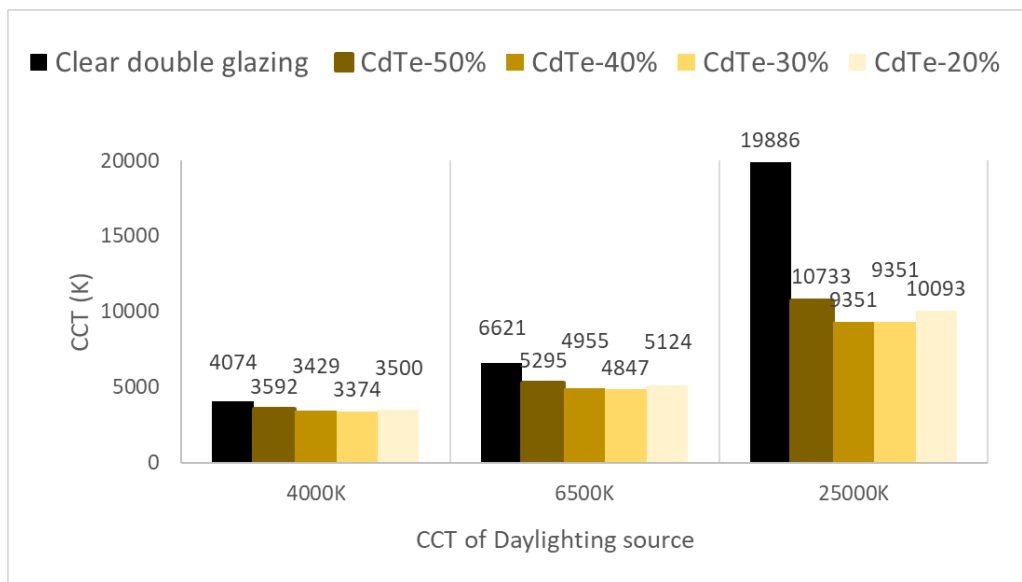
(b)

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)

1 Fig. 10 shows the variation of CCT of the transmitted light through the four types of the CdTe  
 2 PV windows and also the clear double glazing under three daylight scenarios. For the 4000K  
 3 and 6500K daylight scenarios, clear double glazing has negligible influence on CCT. When the  
 4 CdTe PV windows are applied, there is a reduction in CCT in the range between approximately  
 5 10%-26% depending on the type used. It can be clearly seen that the colour appearance of  
 6 daylight transmitted through CdTe PV window is classified to be the 'Best' under both 4000K  
 7 and 6500K daylight scenarios, due to CCT falling into the recommended comfortable range  
 8 (i.e. within 3000K-7500K). In the scenario of extreme daylight in summer time where the CCT  
 9 is 25000K, there is an approximately 20% reduction in the CCT for the clear double glazing,  
 10 the CdTe PV windows offer a reduction from approximately 57% to 65% depending on the  
 11 type applied. Although the CCT for the CdTe PV window is still high than 7500K, above the  
 12 upper limit of the comfortable range, it provides a better potential to regulate the transmitted  
 13 light to a better CCT than that of the clear double glazing.

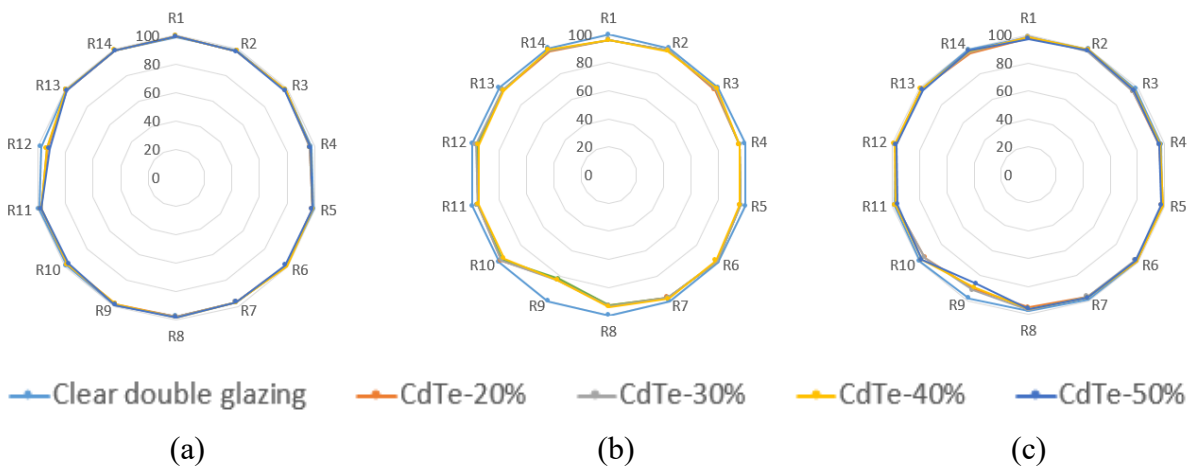


14  
 15 Fig. 10. CCT of transmitted light for CdTe PV window and clear double glazing under three  
 16 daylight scenarios

17  
 18 • *Colour Rendering Index (CRI) for CdTe PV window*  
 19

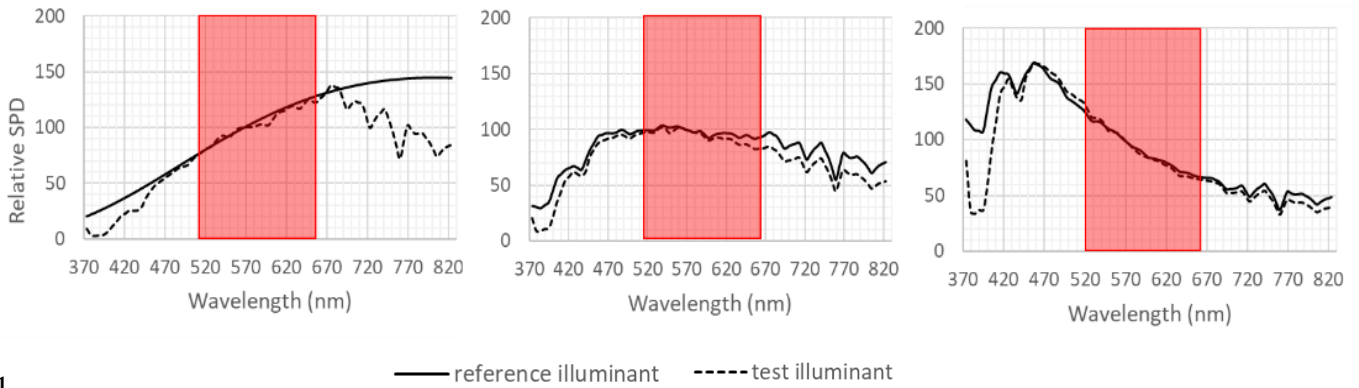
20 To explore the colour rendering properties of the CdTe PV windows, Ri for the 14 standard test  
 21 colour samples (R<sub>1</sub> to R<sub>14</sub>) of CdTe PV window and clear double glazing are plotted into radar  
 22 charts under three daylight scenarios as shown in Fig. 11. From Fig. 11, it can be seen that for  
 23 all the three scenario, clear double glazing and CdTe PV windows can achieve a CRI higher  
 24 than 95 for the front eight-test colour (R<sub>1</sub> to R<sub>8</sub>). It is also found that under the 6500K daylight

1 scenario, CdTe PV window has relative poor ability to render R<sub>9</sub> (strong red) as the CRI of  
 2 CdTe PV windows for R<sub>9</sub> are all below 85 under 6500K daylight. According to Lin et al. [54],  
 3 the spectral power distortion of the test illuminant in the wavelength range between 520nm-  
 4 665nm has significant effect on the CRI value for R<sub>9</sub>. Fig. 12 shows the relative SPD of the test  
 5 illuminant for CdTe-50% and the corresponding relative SPD of reference illuminant under three  
 6 daylight scenarios. The largest deviation of relative SPD between test and reference illuminant  
 7 within the 520 -665 nm (as highlighted with red block on the Fig. 12) can be observed in the  
 8 6500K scenarios. It explains why under 6500K daylight, the colour rendering capacity of CdTe  
 9 PV window on the R<sub>9</sub> (strong red) is weaker than them under 4000K and 25000K daylight. Fig.  
 10 13 shows the overall CRIs for all the CdTe PV windows and clear double glazing. It clearly  
 11 illustrates that all the four types of CdTe PV window are able to achieve the best colour  
 12 rendering as their Ra are all higher than 95. This is because that the general CRI only accounts  
 13 for the front eight-test colour samples which are all awarded a high CRI as shown in Fig. 11.  
 14 The findings suggest that the CIE CRI might not be a comprehensive indication for the colour  
 15 rendering evaluation as it only considering the colour rendering evaluation for unsaturated  
 16 colour (i.e. the front eight test colour samples). For the light source such as the daylight  
 17 transmitted through CdTe PV window, it may have a poor performance on the colour rendering  
 18 of the saturation colour even though they can have a high performance on the colour rendering  
 19 of the unsaturated colour.



23 Fig. 11 Special CRI of CdTe PV window and clear double glazing (a) 4000K scenarios (b)  
 24 6500K scenarios (c) 25000K scenarios.

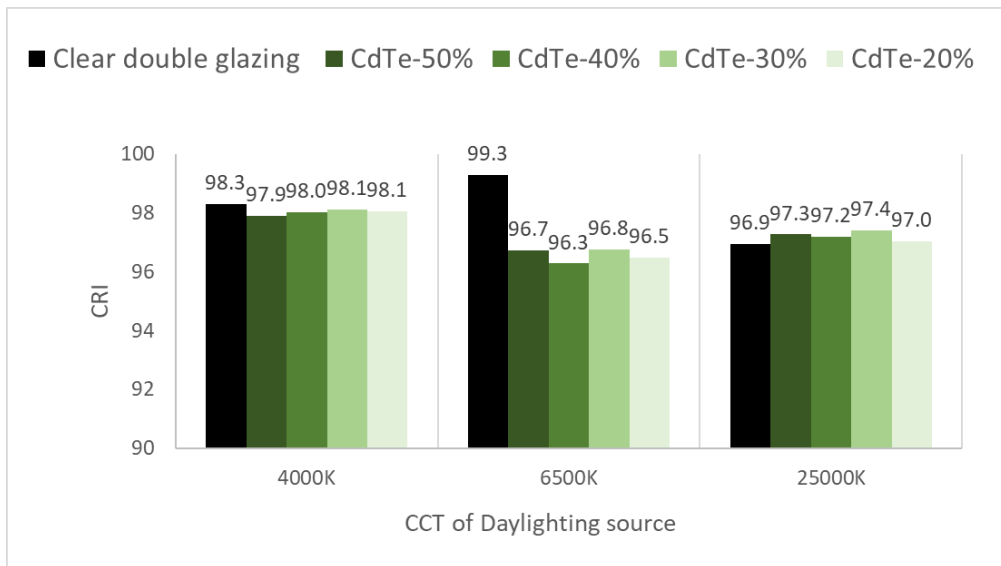
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(a) (b) (c)

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



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7  
8

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

## 9 5. Summary

10 The overall assessments under all the criteria for CdTe PV windows with different transparency  
 11 and the reference double-glazing window with 2 WWRs have been shown in Table 2 and 3. All  
 12 the criteria are classified into four ranks, ‘Best’, ‘Good’, ‘Reasonable’ and ‘Unreasonable’. The  
 13 four ranks for glare, colour appearance and colour rendering have been specified in the section  
 14 2 respectively. It is well known that a higher percentage of working hours for  $UDI_{100-2000 \text{ lux}}$  or  
 15  $U_o \geq 0.7$  is expected to offer better luminous comfort, however, there are no ranks of the  
 16 percentage of working hours for these in comparison to other daylight metrics. To match the



1 ranks of glare, colour appearance and colour rendering, the percentages of working hours for  
2  $UDI_{100-2000\text{ lux}}$  and  $U_o \geq 0.7$  also have also been classified into four ranks. According to Acosta  
3 et al. [55], a best design for daylight autonomy requires the percentage of working hours for  
4  $UDI_{100-2000\text{ lux}}$  to be higher than 70%. Therefore, average  $UDI_{100-2000\text{ lux}}$  higher than 70% is  
5 classified to be the 'Best'. If the percentage of working hours for average  $UDI_{100-2000\text{ lux}}$  is less  
6 than 50%, the period for occupant dissatisfaction with the luminous environment is longer than  
7 the period for occupant satisfaction. Therefore, when average  $UDI_{100-2000\text{ lux}}$  is less than 50%,  
8 daylight availability for the luminous environment is classified to be 'Unreasonable'.  
9 Correspondingly, 60% of working hours are used as the threshold to classify 'Good' and  
10 'Reasonable'. For daylight distribution, similarly, 70%, 60% and 50% of working hours are the  
11 thresholds for classifying the 4 ranks of  $U_o \geq 0.7$ . In Tables 2 and 3, dark green block means  
12 that the window type in the left column meets the 'Best' rank for the criterion in the top row.  
13 Light green block means it meets the 'Good' rank for the criterion. Yellow and red blocks  
14 indicate the related window types meet 'Reasonable' or 'Unreasonable' ranks for the criteria  
15 respectively. As shown in Tables 2 and 3, all the window types are classified to be 'Best' for  
16 both colour appearance and colour rendering criteria. For WWR 60%, CdTe-20% and CdTe-  
17 30% demonstrates the best performances as all of the criteria have reached 'Best' or 'Good'  
18 ranks, while clear double glazing performs the worst. Although CdTe-40% and CdTe-50%  
19 result in the most uniform daylight distribution on the task area, they only achieve 'Reasonable'  
20 rank for daylight availability. In addition, CdTe-50% provides 'Unreasonable' rank for glare  
21 due to over 16.4% of working hours suffer from intolerable glare with the integration of CdTe-  
22 50%. For WWR 30%, as shown in Table 3, CdTe-40% and CdTe-50% have the best  
23 performance among all these window types, due to the ranks for all the criteria for CdTe-40%  
24 and CdTe-50% are better than or equivalent to 'Reasonable'. Clear double glazing still presents  
25 the worst performance. For CdTe-20% and CdTe-30%, they can give rise to the highest daylight  
26 availability and also can significantly reduce the risk of glare caused by daylight. However,  
27 they result in less uniform daylight distribution on the task area, i.e.  $U_o > 0.7$  reduced from 39%  
28 for clear double glazing to approximate 30% for CdTe-20% and CdTe-30%.

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1 Table 2 Rankings of different types of window under all the criterial factors under 60%  
 2 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	
<b>Clear double glazing</b>	Average UDI <sub>100-2000 lux</sub> =34%	DPG <sub>≤0.45</sub> = 63.1%	U <sub>o ≥0.7</sub> = 69.4%	CCT=6621K	CRI=99.3	5
<b>CdTe-20%</b>	Average UDI <sub>100-2000 lux</sub> =69%	DPG <sub>≤0.35</sub> = 98.4%	U <sub>o ≥0.7</sub> = 65.6%	CCT=5295K	CRI=96.7	1
<b>CdTe-30%</b>	Average UDI <sub>100-2000 lux</sub> =64%	DPG <sub>&lt;0.4</sub> = 93.6%	U <sub>o ≥0.7</sub> = 66.9%	CCT=4955K	CRI=96.3	2
<b>CdTe-40%</b>	Average UDI <sub>100-2000 lux</sub> =59%	DPG <sub>&lt;0.4</sub> = 92.4%	U <sub>o ≥0.7</sub> = 70.7%	CCT=4847K	CRI=96.8	3
<b>CdTe-50%</b>	Average UDI <sub>100-2000 lux</sub> =50%	DPG <sub>≤0.45</sub> = 83.6%	U <sub>o ≥0.7</sub> = 72.6%	CCT=5124K	CRI=96.5	4

\* Indications of ranks in the table



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

Under 30% WWR	Daylight Quantity	Daylight Quality				Overall ranking
Window type	daylight available	Glare	distribution	Colour quality (6500K scenarios)		
				Colour appearance	Colour rendering	
<b>Clear double glazing</b>	Average UDI <sub>100-2000 lux</sub> =56%	DPG <sub>≤0.45</sub> = 89%	U <sub>o ≥0.7</sub> = 38.7%	CCT=6621K	CRI=99.3	5
<b>CdTe-20%</b>	Average UDI <sub>100-2000 lux</sub> =71%	DPG <sub>≤0.35</sub> = 99.5%	U <sub>o ≥0.7</sub> = 28.9%	CCT=5295K	CRI=96.7	3
<b>CdTe-30%</b>	Average UDI <sub>100-2000 lux</sub> =70%	DPG <sub>≤0.35</sub> = 97.8%	U <sub>o ≥0.7</sub> = 29.2%	CCT=4955K	CRI=96.3	4
<b>CdTe-40%</b>	Average UDI <sub>100-2000 lux</sub> =68%	DPG <sub>≤0.35</sub> = 96.9%	U <sub>o ≥0.7</sub> = 50.1%	CCT=4847K	CRI=96.8	1
<b>CdTe-50%</b>	Average UDI <sub>100-2000 lux</sub> =65%	DPG <sub>&lt;0.4</sub> = 93.8%	U <sub>o ≥0.7</sub> = 50.9%	CCT=5124K	CRI=96.5	2

\* Indications of ranks in the table



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 7

## 1 **6. Conclusions**

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

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

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

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

31

## 1 Acknowledgments

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## 4 References

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