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Performance assessment of cadmium telluride-based semi-transparent glazing for power saving in façade buildings

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Citation:

1 # **Performance Assessment of Cadmium Telluride-based Semi-**
2 # **Transparent Glazing for Power Saving in Façade Buildings**

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14 **Abstract:**

15 Façade buildings are generally highly glazed and energy-intensive especially in countries
16 with hot weather. Power consumption in these buildings is even more significant when air
17 conditioning (AC) is added to the figures. Building with semi-transparent photovoltaic
18 (STPV) materials is bringing advantageous energy-saving features to these façade structures.
19 Energy is saved by more heat being reflected resulting in less AC power consumption with
20 the STPV thermal properties. In addition, the optical and electrical properties provide indoor
21 sunlight with power generation. This paper investigates the net potential energy saving via
22 applying cadmium telluride (CdTe) in Façade buildings. The analysis has been carried out
23 using indoor and outdoor experiments considering different orientations and transparencies.
24 Compared to a single glazing case as a reference, the application CdTe achieved a net energy
25 saving to be as high as 20%. Furthermore, a trade-off between saving energy and
26 environment comfort has been discussed as less transparency windows lead to more artificial
27 light consumption. The findings indicate that STPV is a promising solution for sustainable
28 buildings.

29 **Keyword**: Thin Film Glazing, CdTe, Façade Building, Energy performance

30

31 **HIGHLIGHTS**

32 • Performance assessment of CdTe-based STPV for saving Façade buildings power

33 • Calculation, evaluation, and comparison of different glazing and its effect on the air
34 conditioning power and temperatures

35 • Estimation the lighting energy consumption for different glazing

36

1. Introduction

Currently, the transport sector has the highest percentage of total primary energy consumption in the world. However, further scenarios of the International Energy Agency (IEA) indicate that the domestic sector will lead the total consumption by 2035 ("International Energy Agency, World Energy Statistics and Balances 2017," n.d.). Therefore, there is a great necessity to develop solutions that minimize heat transfer through buildings to their surrounding areas.

The increase in attention to the aesthetic aspects of buildings leads to the adoption of highly glazed fronts for façade and high-rise buildings. The roof area of a high-rise building is a lot less compared to a facade. Therefore, installing a photovoltaic system is an option for facades. However, the building is still considered energy intensive because of the comparison of the available area and the generated solar energy.

Another aesthetic aspect is windows. Windows play a significant role in buildings. Not only do they provide visual comfort, but they also reflect the environment thermally and optically (Baldinelli et al. 2014). Windows influence on energy loss from buildings becomes much more drastic when the window area is large like patio doors (Cuce, Young, and Riffat 2014). Current conventional residential windows are responsible for around 47% of heat loss because of the building fabric (Cuce, Young, and Riffat 2015). Due to being able to reduce the heat requirement and energy consumption of buildings the significance of windows is given considerable attention for improvement.

Recently, Semi-Transparent Photovoltaics (STPV) solar cells have been developed and are popular in research (Peng et al. 2016; Chen et al. 2012; Fung and Yang 2008; Miyazaki, Akisawa, and Kashiwagi 2005; Olivieri et al. 2015; Yoon, Song, and Lee 2011; Yun, McEvoy, and Steemers 2007). This new technology provides relatively light transmittance for a building beside power generation. So adopting it in façade buildings is a promising solution especially when the area of coverage is large, but several factors need to be considered for optimization purposes such as orientation, place of installation, weather conditions, and PV transparency (Catita et al. 2014). Although PV might reflect some heat and reduce the air conditioning (AC) units' consumption, it might also degrade the light intensity inside the building.

Emerging STPV technology such as CdTe has enormous potential, but the BIPV application has not gotten much attention in the available research work. Furthermore, the effects of the angle of incidence on power generation are subject to the place of installation, module orientation, and transparency. This factor has rarely been studied and reported in the energy calculation of the STPV window (Barman et al. 2018).

Through literature research, it was found that most of the research related to PV windows or facades focused on the thermal performance such as the solar heat gain coefficients (SHGC), heat losses, the impact on the air-conditioning cooling load reduction, and energy-saving

potential. In previous literature, little research regarding the overall energy performance rather than on individual thermal or power performance of BIPV windows or facades was reported.

In addition, the effects of orientation and module transparency on power generation, daylight, and heat ingress into the occupant area have been studied by a few researchers (Sharma and Chandel 2013). Plus, some studies provided a performance assessment of using STPV for a specific location (Sharma and Chandel 2013), but a need for a generalized case as an energy assessment tool is crucial. Therefore, it is essential and meaningful to investigate the energy performance of the emerging STPV technology integrated window system.

In this paper, a thermal performance analysis and electrical power saving assessment have been carried out for a CdTe-based STPV integrated window system in the climate of the UK. The experimental process of the power and thermal performance testing was presented in detail. In addition, the thermal performance, which was quantified as solar heat gain coefficient (SHGC) and U-value, was measured and compared for different PV transparencies. Included in the study is the impacts of two key parameters: orientation of the installed STPV and the transparency. Furthermore, the resultant AC units' power consumption reduction in different scenarios has been assessed and compared with a single glazing.

2. PV Cells Properties

In order to investigate the optical properties of the STPV cells (S1, S2, and S3 are shown in figure 1) the transmittance and reflectance were measured using AvaSpec-ULS2048L Star Line Versatile Fiber-optic Spectrometer. The measurements were compared to a clear single glazing, S0. The results are presented below in figures 1 and 2.

Fig. 1: The STPV cells S1, S2, and S3

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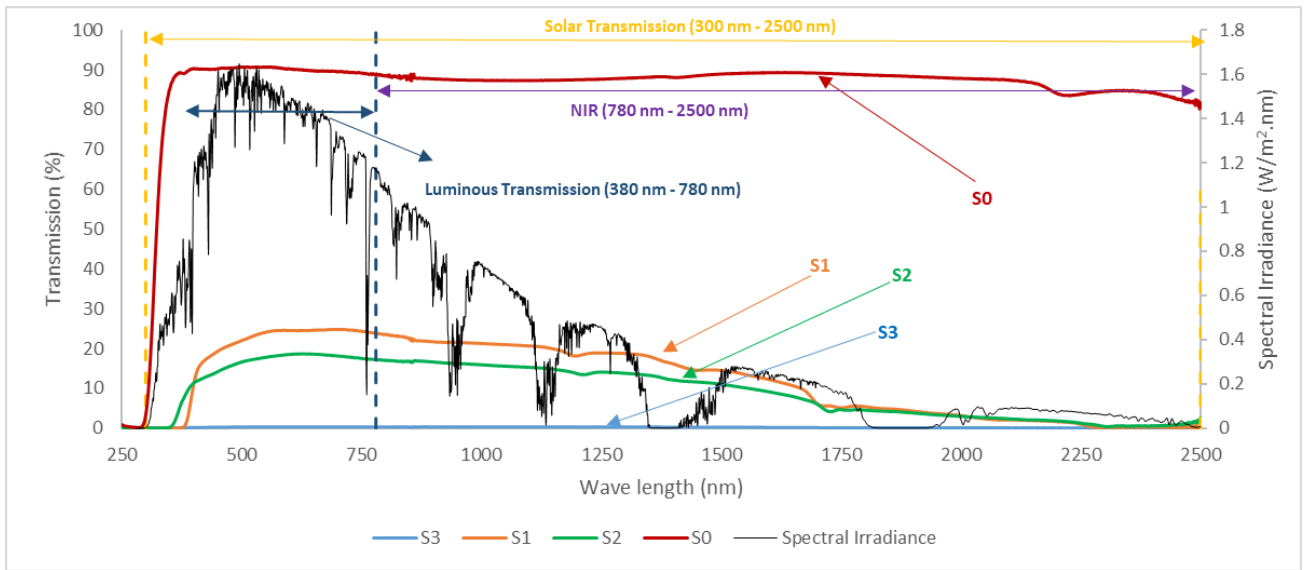
Fig. 2: The Spectral irradiance and transmittance of the STPVs (S1, S2, S3) and the single glazing (S0)

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110 As shown in figure 2, the transmittance of S1, S2, and S3 are 24.83%, 18.66%, and 0.46%,
111 which are less than that of the single clear glazing whose transmittance was 90%. The
112 provision of the difference transparencies is one of thin-film PVs advantages. These results
113 give STPV the opportunity to be used in different applications such as building facades or
114 office room facades in BIPV, windows, and others.

115 Figure 3 shows the reflectance of S1, S2, S3 and the single glazing, S0. Their average values
116 are 15.6%, 15.9%, 16.12%, and 11.97% respectively. All tested PV cells showed almost
117 equal average values of reflectance as well as similar behavior with changing wavelength. At
118 low wavelengths, the reflectance of all PVs showed their minimum values. After a
119 wavelength of almost 1300 nm, reflectance started to increase until reaching maximum
120 values at 2500 nm. However, for the single glazing, reflectance showed more uniform
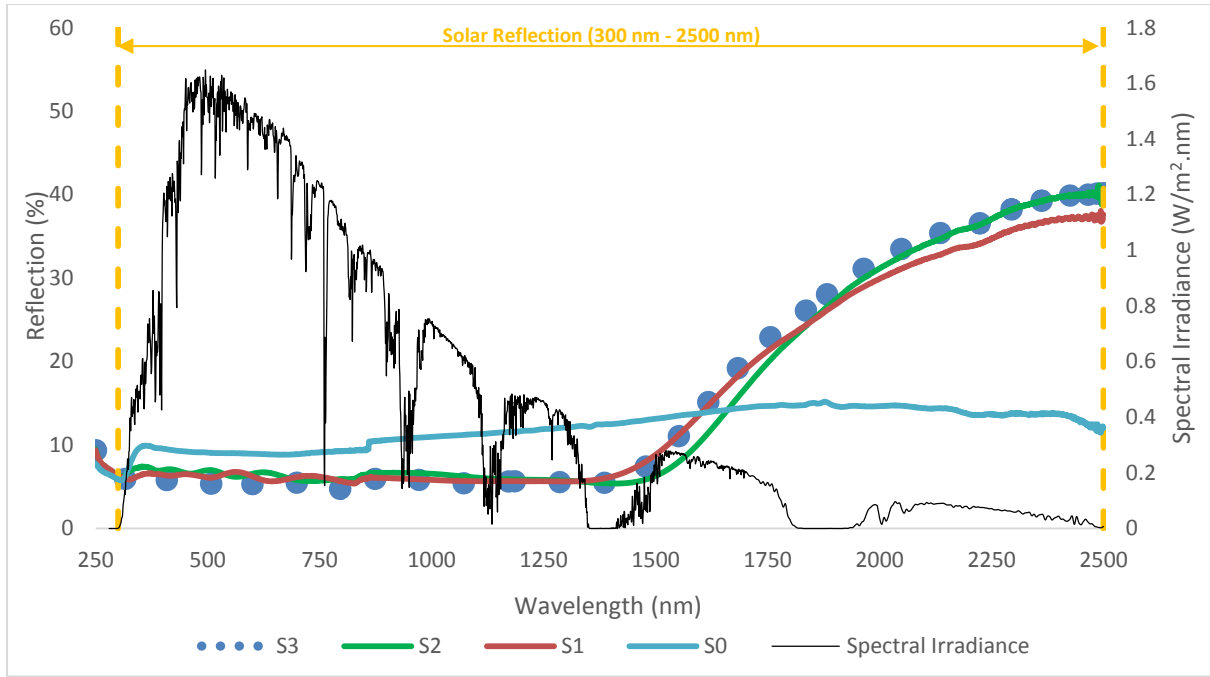121 variation with wavelength than the PVs.

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125   Fig. 3: The spectral irradiance and reflectance of the STPVs and the single glazing

126

127   Two factors that affect heat transfer through the glazing is transmission and reflection. The
128   heat is transferred through three different methods: conduction, convection, and radiation. In
129   radiation, as the fraction of reflected beam in reference to total incident beam increases, the
130   heat transferred through the glazing decreases. In contrast, as the fraction of the transmitted
131   beam in reference to total incident beam increases, the rate of heat transfer increases.

132   Radiation has only three behaviors when passing through a glazing, which are a reflection,
133   transmission, and absorption. Hence, the summation of percentages of the three behaviors
134   gives a value of 100%. Therefore the average absorbance of the above PVs can be calculated
135   and presented in figure 4. The properties of the STPV and the single glazing are summarized
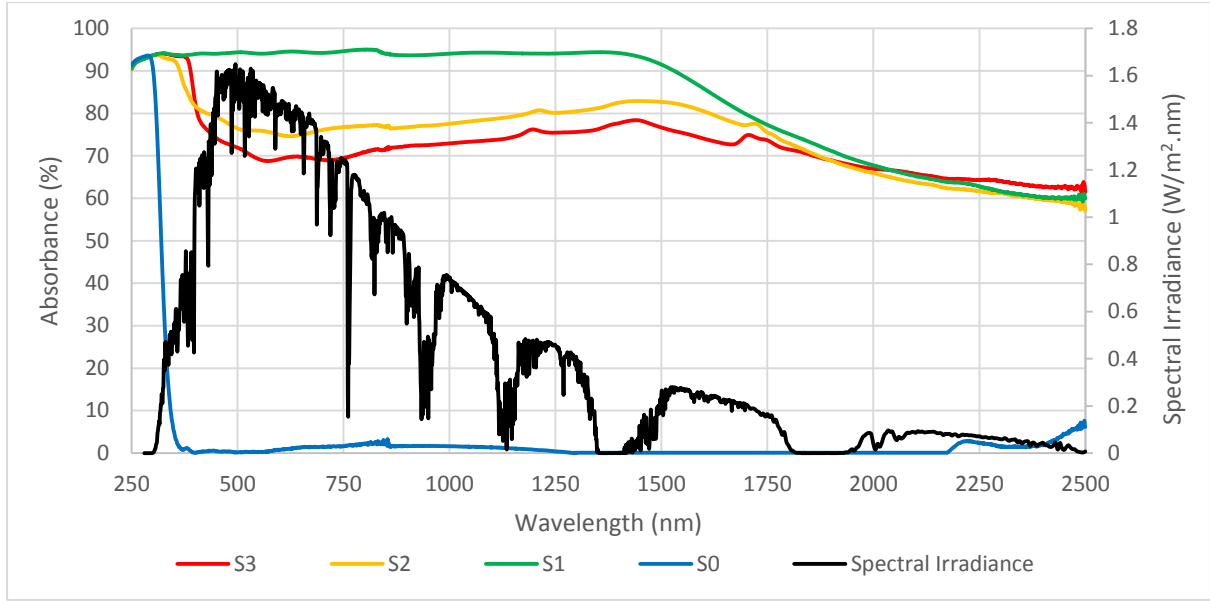136   in table 1.

137

138

Fig. 4: The spectral irradiance and absorbance of the STPVs and the single glazing

Table 1: The properties of a single glazing and STPV

	S3	S2	S1	S0
Maximum Transmittance	0.46%	18.66%	24.83%	90%
Average Transmittance	0.157%	9.3%	12%	85%
Maximum Reflectance	40.37%	40%	41.12%	15.2%
Average Reflectance	16.12%	15.9%	15.6%	11.97%
Maximum Absorbance	95.02%	93.78%	94.11%	93.61%
Average Absorbance	83.6 %	74.74%	72.3%	3.94%

The electrical properties of the STPVs were also investigated using WACOM AAA solar simulator. The IV curves for STPVs used are presented in figure 5. The IV curves reveal that the maximum power point (MPP) of S3 is the highest compared to S2 and S1, which has the lowest value of MPP. Detailed results of STPVs properties are presented in table 2. The results show that the efficiency and power generation were found to be inversely proportional to transmittance. The maximum efficiency and power generation for both orientations was registered for S3 whereas S1 showed the lowest efficiency and power generation.
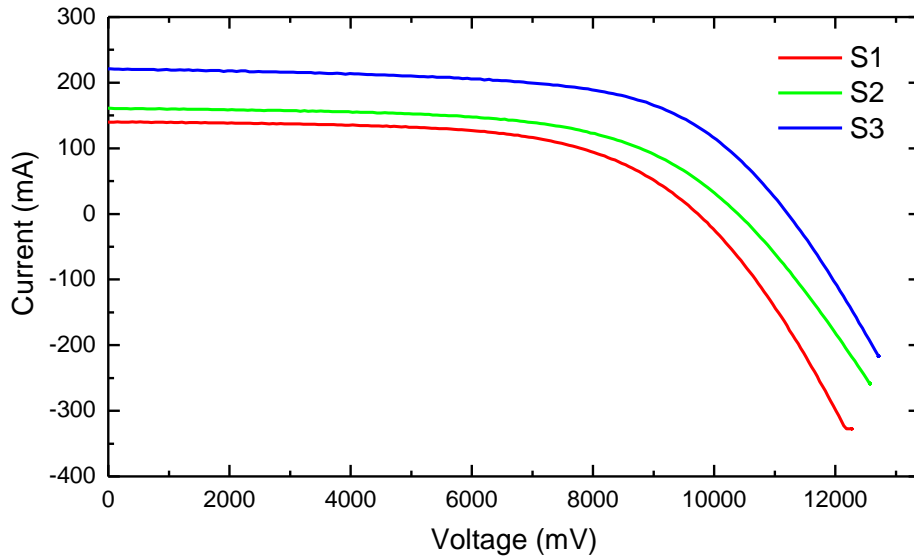
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155   Fig. 5: The IV curve of STPVs used in south-west oriented test cell

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157   Table 2: Electrical properties of STPV cells

Parameters	South West Orientation			South Orientation		
	S3	S2	S1	S3	S2	S1
Nominal Power [Pm] (W)	1.53	0.99	0.815	1.41	0.987	0.815
Short Circuit Current [Isc] (A)	0.22	0.16	0.14	0.21	0.16	0.14
Open Circuit Voltage [Voc] (V)	11.21	10.39	9.734	11.14	10.08	9.734
Current at Maximum Power Point [Imp] (A)	0.18	0.13	0.115	0.163	0.13	0.115
Voltage at Maximum Power Point [Vmp] (V)	8.49	7.57	7.05	8.65	7.43	7.05
Efficiency [η] (%)	12.6	8.23	6.7	11.69	8.15	6.7

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159

160   **3. Methodology**

161   In order to establish a performance assessment for all cells under the same conditions, an
162   experimental setup had been built consisting of eight sample rooms. A data acquisition and
163   logging system had been used to gather data and save it in an excel sheet. The setup was
164   installed at ESI building, Exeter University, UK.

165   The design had two identical sets of four rooms set to the south and south-west directions.
166   Because of the constraint of a fixed size of the available STPV (20 X 20 cm^2) the rooms had
167   been designed with dimensions of 20 X 20 cm^2. It is worth mentioning that the active area of
168   the STPV is within the 10 X 10 cm^2.

169   Each room had insulated sides made of polystyrene sheets (thickness of 2.5 cm) to provide
170   good insulation so that we could neglect any side thermal disturbances except for one side,

171 which represented the window. The rooms utilized Peltier-based cooling systems for
172 mimicking the AC units in the buildings. Also, each room was equipped with:

173   -   K-type temperature sensors, outer and inner cell surfaces inside the room for
174   thermal evaluation
175   -   a light sensor in the middle of the room
176   -   voltage and current sensors for AC power consumption measurements
177   -   a voltage sensor for the STPV power generation measurement
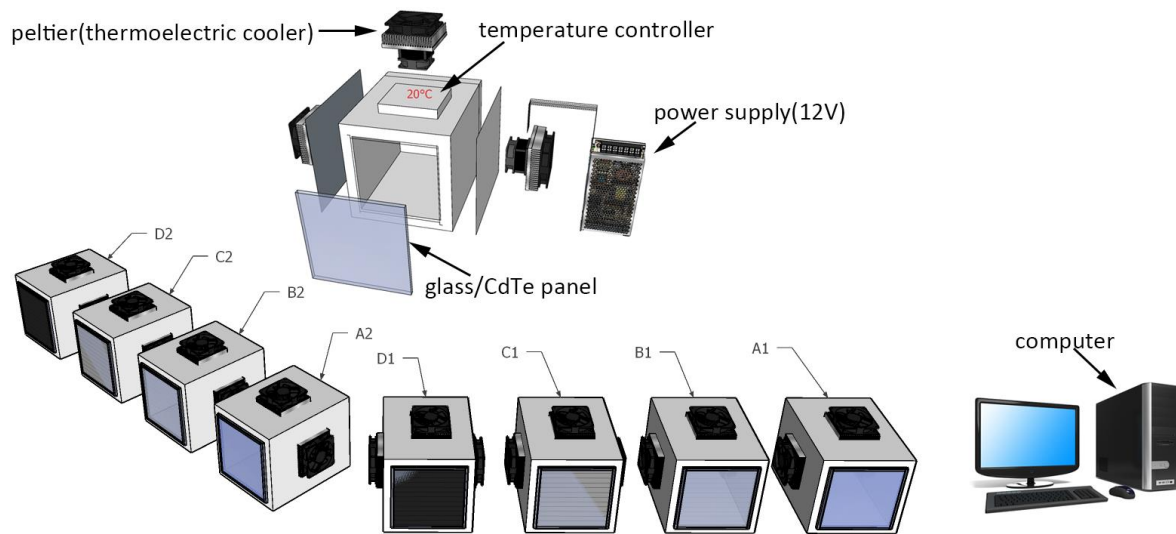
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181 Fig. 6: The schematic diagram of the experimental setup.

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183 All rooms are installed in a box provided by ventilation holes and fans. Figure 7 shows the
184 completed experimental setup. Also, each room can be tested individually indoor under the
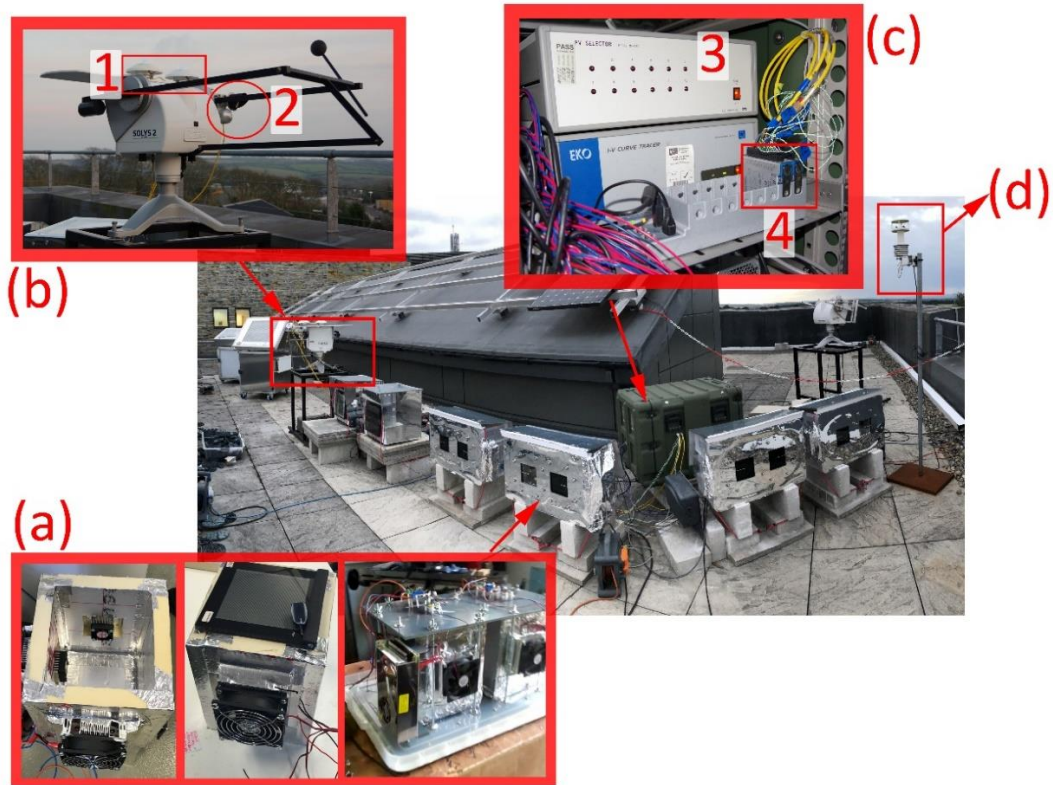185 AAA solar simulator to provide different radiation conditions.

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Fig. 7: The Completed view of the whole setup: (a) test cell (b) solar tracker (1) global and diffuse radiation (2) the direct radiation (c) data logger (3) IV-tracer (4) thermocouple data logger (d) weather station

The indoor experiments were carried out on each room by thermal performance evaluations and for AC power consumption assessments under various irradiances with different transparencies.

Outdoor experiments were dedicated to the overall system energy evaluations in real weather. The evaluations included orientation aspects, wind and shading disturbances, and inside-light measurement when the facades were vertically assembled.

4. Thermal properties evaluation

The U-values and SHGC of the tested glazing are presented in Table 3 below. In the results, if S_0 has the highest U-value among all the tested cells, then the other cells can be arranged in descending order of U-value as S_1, S_2, and finally S_3. This pattern is applicable for both the south and south-west orientations. As for the SHGC, S_0 was shown to have the highest value in both orientations. The other glazings of SHGC can be arranged again in descending order as S_1, S_2, and S_3. Nevertheless, table 3 demonstrates the effects of orientation on the insulation properties of the glazing.

208

209   Table 3: The U-values and SHGC of the tested glazing

SPTV/Glass	U-value in South Orientation	U-value in South West Orientation	SHGC in South Orientation	SHGC in South West Orientation
S_0	5.6 W/m^{2}K	5.58 W/m^{2}K	0.105	0.113
S_1	3.2 W/m^{2}K	2.85 W/m^{2}K	0.0958	0.1043
S_2	2.7 W/m^{2}K	2.5 W/m^{2}K	0.095	0.1039
S_3	0.25 W/m^{2}K	0.49 W/m^{2}K	0.0944	0.1032

210

211   The U-values and SHGC values in the south orientation are slightly larger than that of the
212   south-west, which is because of the difference in solar irradiance. The change in U-value and
213   SHGC leads to a significant shift in cooling and heating demands. As these values increase,
214   the cooling load increases and the heating load decreases. Therefore, to have the best thermal
215   insulation in cold climate regions, it is preferable to use high U-values in the south orientation
216   so that lower heating load is needed. However, in hot climate regions, the use of such
217   systems can lead to excessive cooling load.

218

219   **5. Room temperature and Air conditioning**

220   As per Lomas and Kane (Lomas and Kane 2013), the range of comfort temperature in winter
221   and summer seasons is below 24°C. Also according to Seppanen, Fisk, and Lei (Seppanen,
222   Fisk, and Lei 2006), the performances increase with temperatures up to 22°C and decreases
223   with temperatures above 24°C. In this trial, the thermostat was set at 20°C for cooling to
224   calculate the AC loads. According to the UK weather, keeping the inside temperature of the
225   room below 20°C is not hard. However, in hot countries, i.e. in the Middle East, it needs the
226   AC to work for a longer time with higher capacity to achieve the 20°C regulation.

227   The Fig. 8, Fig. 9, and Fig. 10 depict the temperature profiles for three different days; 6 May
228   2018, 23 NOV 2017, and 12 DEC 2017 respectively. These figures show that for hot days in
229   May the AC units needed to work harder and longer than the other days in November and
230   December. On those days in November and December, the units were hardly required or not
231   at all. On the November 23rd sample, the AC in rooms with S0 and S1 ran for a short period
232   during the day, while rooms with S2 and S3 kept the temperature below 20°C. This
233   contributes to the objective of the paper and the feasibility of using STPV. To emphasis the
234   value of saving even more, sample days that has relatively higher temperature profiles will be
235   selected between May to September over the year.
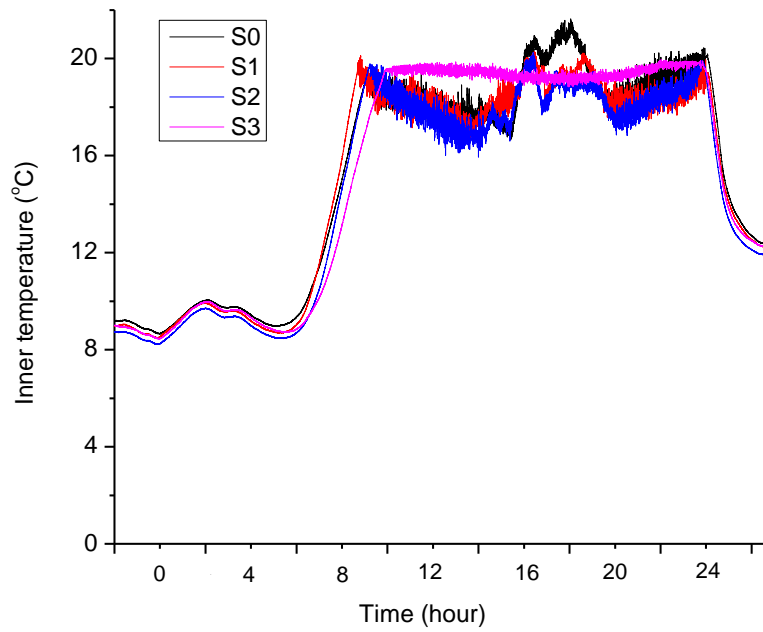
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239   Fig. 8: The inner-temperature profiles of the south-facing rooms on 6 May 2018
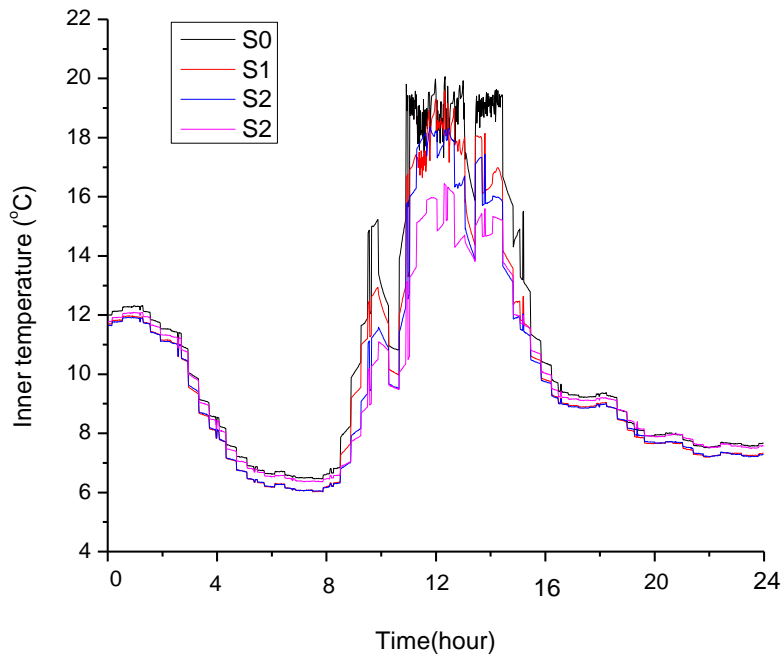240

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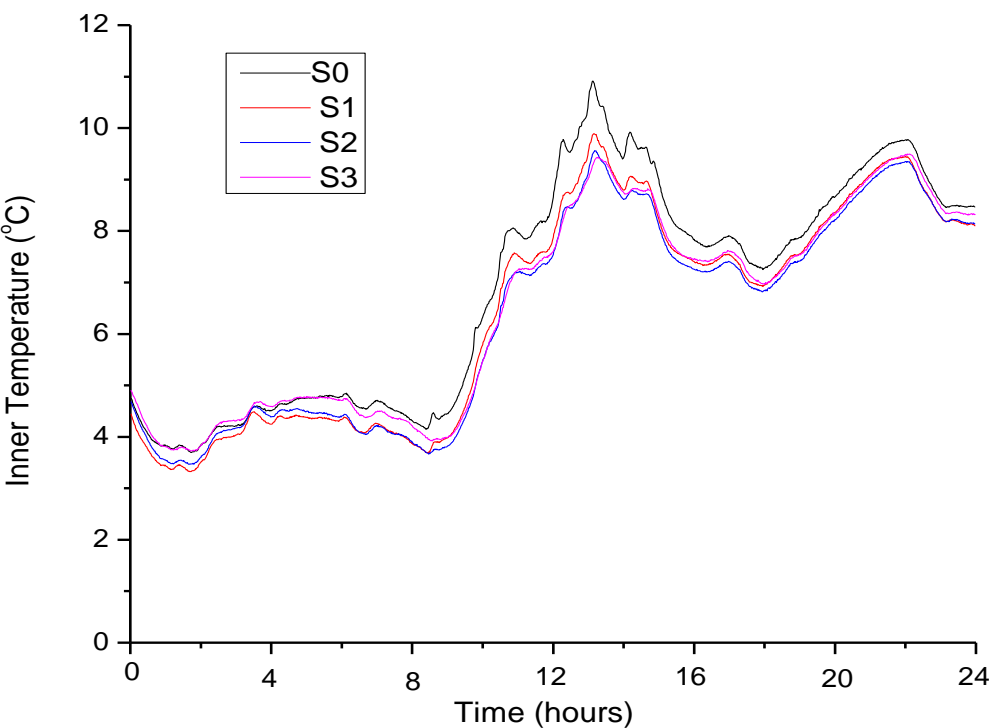243   Fig. 9: The inner-temperature profiles of the south-facing rooms on 23 November 2017
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Fig. 10: The inner-temperature profiles of the south-facing rooms on 12 December 2017

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6. Results and discussion

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6.1. AC power consumption

The power consumption data has been recorded during the May sample day for the four rooms in both directions: south and south-west.

Fig. 11 shows the accumulated energy consumption over the twenty-four hour period for both orientations with the various transparencies. The consumption of the S0 room in both orientations is proven to be the most while S3 is the least. Respectively, the energy savings for S1, S2, and S3 compared to the reference room S0 are 4.8%, 8.6%, and 11.6% for the south orientation and 7.9%, 14.4%, and 23.2% for the south-west-oriented rooms.
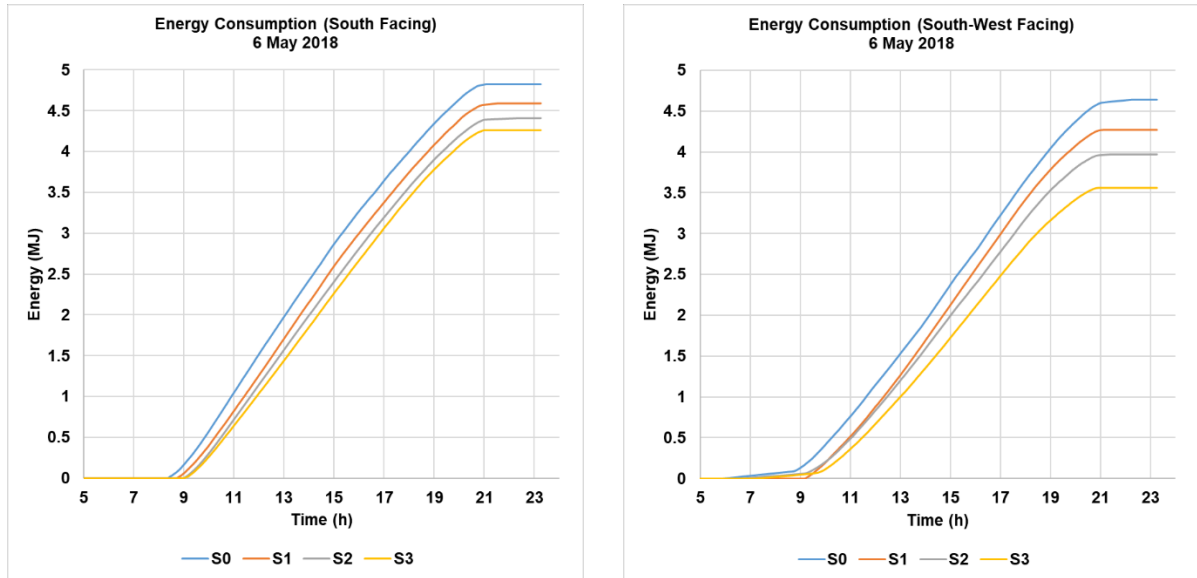
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Fig. 11: The AC energy consumption for different orientations and different transparencies on 6 May 2018

It was noticed that the consumption of the south-west oriented S0 room is slightly less than the south-oriented, which is close to the south-west oriented S1 room, yet the power consumption savings is relatively twice for the south-west rooms. This is because the south rooms are facing the sun for more extended periods of time with higher radiation, which transfer more heat inside the rooms. Therefore, the south rooms require more cooling energy for all STPVs.

A caveat can be concluded for very hot weathers and south-facing facades, but the savings could be insignificant. This is also shown for the power consumption on 24 November in Fig. 12, which is a relatively colder day. The energy saving figures for that day are 43.5%, 54.5%, and 61.1% for the south-facing S1, S2, and S3 rooms respectively.
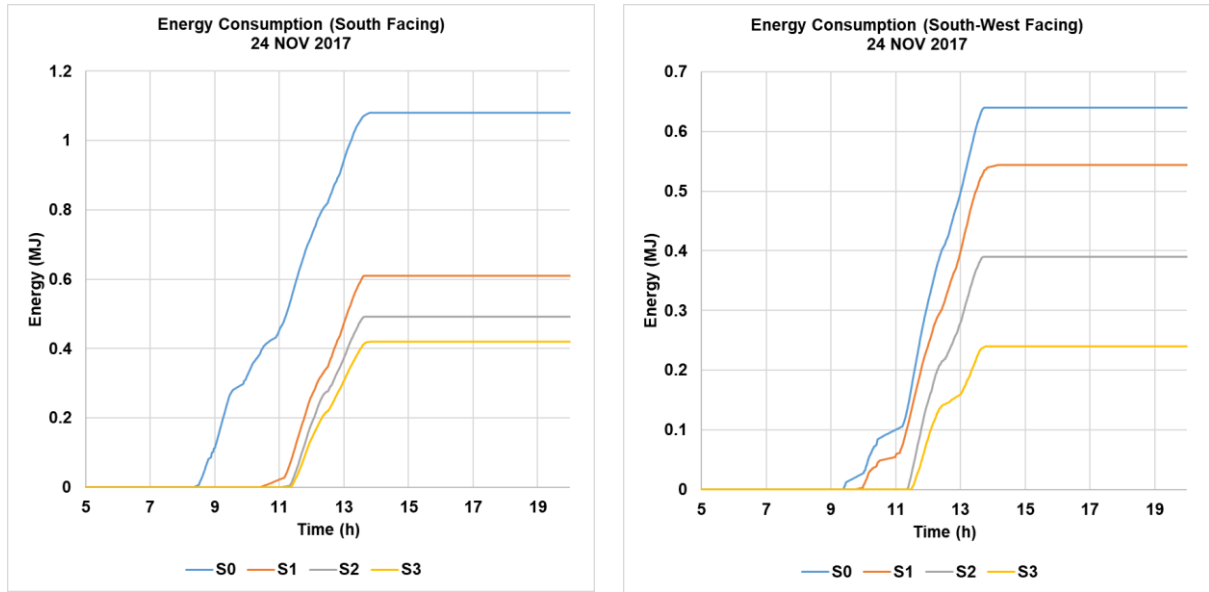
Fig. 12: The AC energy consumption for different orientations and different transparencies on 24 Nov 2017

Furthermore, the working hours for the AC units in May is about thirteen hours while it is six hours in November. This contributes to more savings in November than May. According to the finding by Barman, Chowdhury, S. Mathur, and J. Mathur [14], the determining factors for cooling loads, U-value and SHGC, for window systems are higher than for the opaque wall. Therefore, as the window to wall ratio (WWR) increases, the thermal load of the building rises.

6.2. STPV generation

Instead of the clear glazing, using STPV introduces more reflectance and absorption to the visual light penetrating the windows. Therefore, less sunlight will serve the interior lighting during the working hours and more artificial light consumption will be required. Fig. 13 illustrates the direct, diffused, and global irradiance on 6 May, which reflects a relatively sunny day.
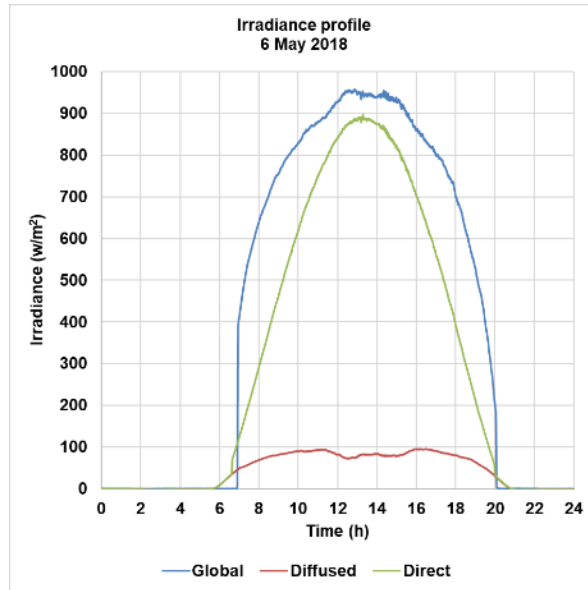
Fig. 13: The direct, diffused, and global irradiance on 6 May 2018

As the STPVs are used to decrease the heat transfer to the building and save cooling energy, they also contribute to power generation. For example, the S1 STPV sample can generate 30 kJ of energy, which can be directly used by some loads or stored in energy storage systems. This amount of energy is small when it is compared with the AC power consumption, which on the same day, exceeded the 4.5 MJ as shown in Fig. 11. The calculated average power and accumulated energy generation of the S1 STPV results are shown in Fig. 14. Moreover, the solar PV module has the same area and reflectance as the STPVs, but because of the modules lesser transmittance it absorbs more radiation. This is subsequently converted into electrical energy. Therefore, the S2 and S3 are expected to provide more power of up to 70% of the S1 production, which is limited to 51 kJ. These energy generations are expectable from the finding in a previous research work (Peng et al. 2016).
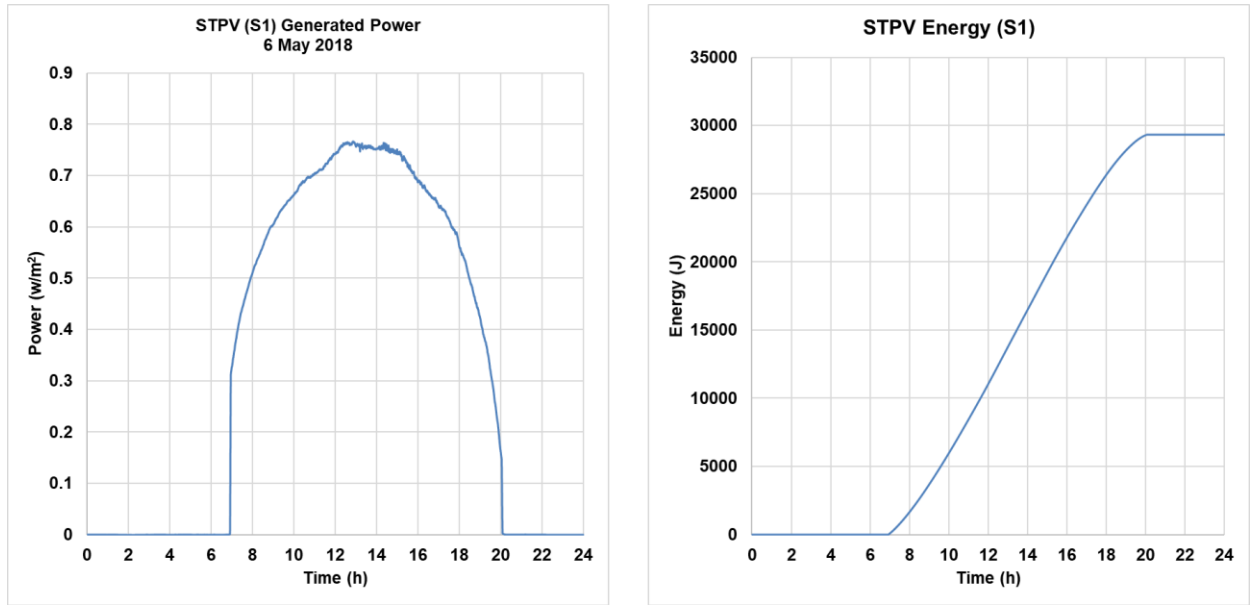
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314   Fig. 14: The generated power and energy of the S1 STPV room

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317   *6.3.Interior lighting compensation*

318   In UK standards, the lighting requirement for a façade building for offices is about 500
319   lumen/m^2 (Butcher, Craig, and Chartered Institution of Building Services Engineers, n.d.).
320   This can be translated into 9 – 13 W/m^2 if tubular fluorescent lighting is used (Jenkins and
321   Newborough 2007). For twelve hours (7 am to 7 pm) a 10 W/m^2 had been chosen as the
322   average required value. With an artificial lighting dimming control system introduced the
323   artificial lighting will be activated and reach the required illuminance level, with the extra
324   electricity consumption calculated when the daylight illuminance level is below 500 Lux.

325   Fig. 15 shows the required irradiance and the available interior irradiance for one of the
326   rooms, which has window S1 with the highest STPV transparency. It is evident that the
327   available light can meet the required value for a short time on that sunny day (6 May 2018).
328   However, it does need some artificial lighting to satisfy the entire duration. Also, for cloudy
329   days or winter days, the expectations from the penetrated sunlight is less.
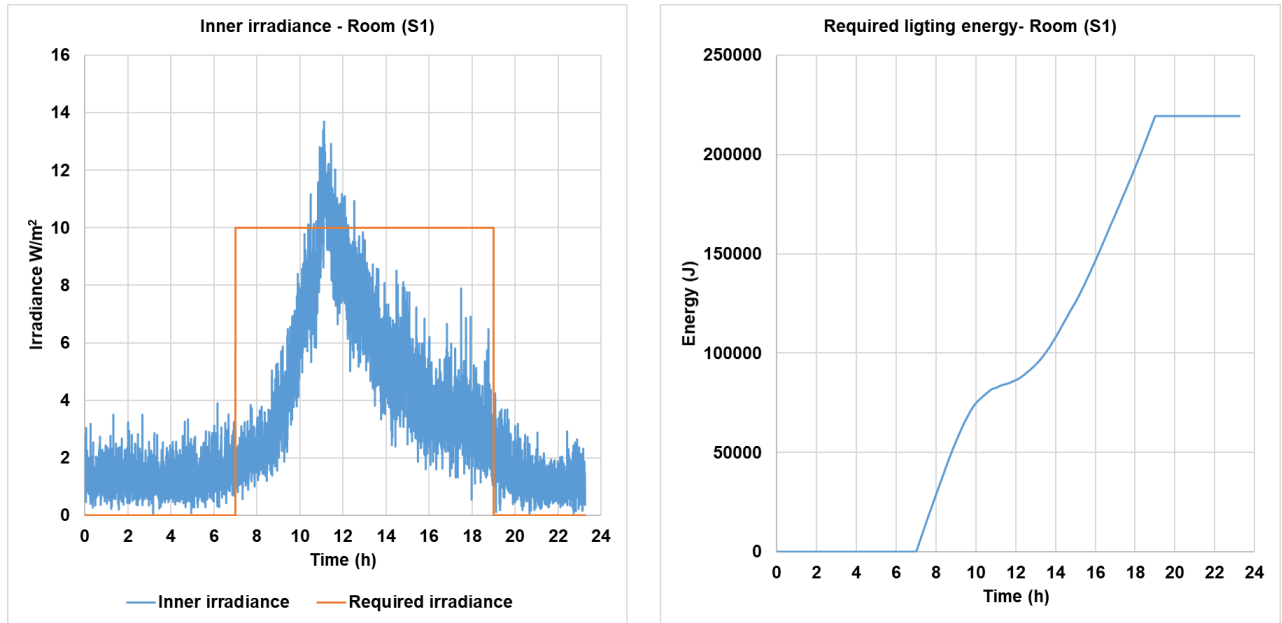
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Fig. 15: The inner irradiance of the room (S1) and the required lighting energy

The required lighting energy using 10 W/m^2 as a reference, has been calculated during the twelve hours as shown in Fig. 15. In total, 220 kJ is needed.   The generated energy from S1 STPV as shown in Fig. 14 might be used to cover a portion of this consumption, which represents 13.1%. This saving will be less with the lower transparency STPV (S2 and S3) as less sunlight is allowed to penetrate.

6.4.Net energy performance

The effects of the STPV window systems on the net energy performance has been analyzed by using the following relation:

Net energy performance = AC energy consumption + Artificial lighting energy consumption − STPV energy generation

Fig. 16 shows the net energy performance for both orientations and all STPV transparencies-based rooms considering the rooms (S0) as references.   The AC power consumption decreases with lower transparency PVs. For the south-facing rooms, the S1, S2, and S3 consumption relative to S0 are 4.85%, 8.6%, and 11.6% less respectively, while the figures are 7.97%, 14.4%, and 23.27% for the south-west oriented-rooms. Furthermore, more details are found in Table 1.
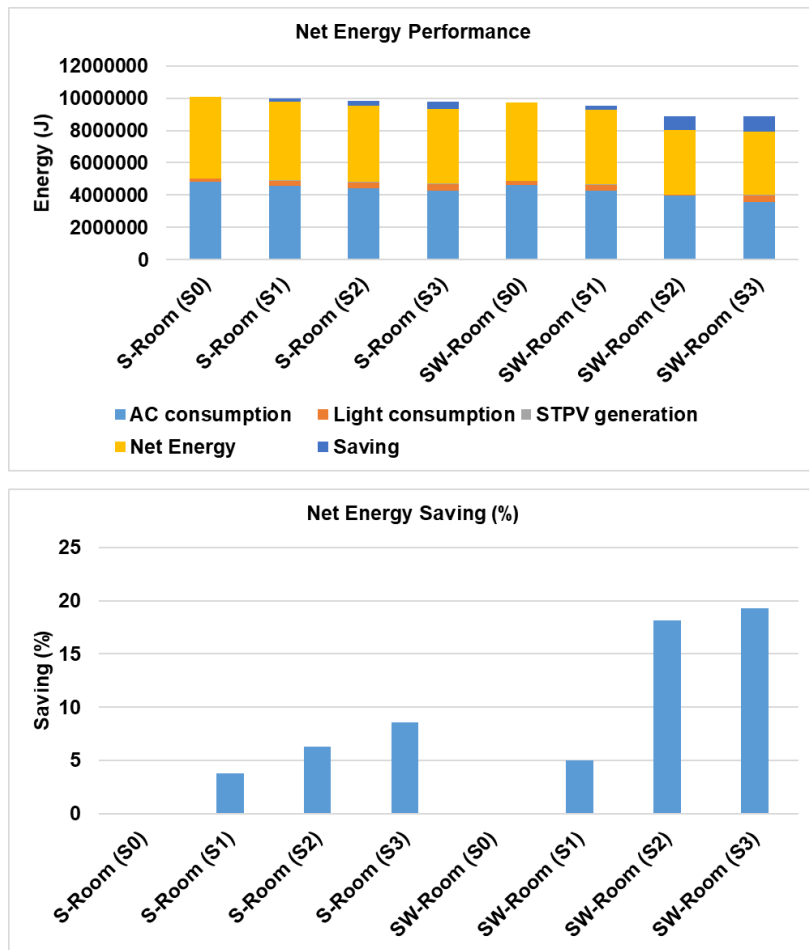
Fig. 16: Net generation performance

The clear glazing allows more sunlight to serve the interior lighting of the rooms, while STPV introduces shading and reflection so that less sunlight penetrates. Thus, more lighting consumption is observed to be used relative to the S0 rooms. The results are 33.3%, 60.4%, and 82.9% more for the S1, S2, and S3 south rooms respectively. The south-west rooms figures are 67.3%, 82.2%, and 83.7% more for S1, S2, and S3.

Compared to the total power consumption of the single glazing S0 case, the energy savings for S1 is about 3.77%, S2 is 6.28%, and S3 is 8.5% for the south facing rooms while the savings are 5% for S1, 18.1% for S2, and 19.2% for S3 south-west facing rooms. The saving of the south-west rooms compared to the south rooms are 4.86% for S1, 15.77% for S2, and 14.86% for S3. Therefore, installing this technology is promising for south-west faces.

Lastly, it is essential to consider the friendly environment and health sides for the residents. Using low transparency PVs might affect health issues and mental states (Aries, Veitch, and Newsham 2010). As a trade-off, using the S1 sample on the south-west facing windows might be a good choice according to the results in

Table .

Table 4: The net energy saving

	South-facing Rooms				South-West-facing Rooms			
	(S0)	(S1)	(S2)	(S3)	(S0)	(S1)	(S2)	(S3)
AC consumption (MJ)	4.825	4.591	4.410	4.263	4.640	4.270	3.970	3.560
Light consumption (kJ)	219.3	292.4	352.0	401.2	222.2	371.8	395.9	408.3
STPV generation (kJ)	0	293.3	348.3	524.2	0	234.6	278.6	419.4
Net Energy (kJ)	504.4	485.4	472.7	461.1	486.2	461.8	398.1	392.6
Saving (kJ)	0	190.1	317.1	432.5	0	243.8	880.5	935.8
Saving (%)	0	3.77	6.28	8.57	0	5.01	18.10	19.24

7. Conclusion

In this paper, a thermal performance analysis and electrical power saving assessment have been carried out for a CdTe-based STPV integrated window system in the climate of the UK. The experimental results of the power and thermal performance testing were presented in detail. The thermal performance, which was quantified as solar heat gain coefficient (SHGC) and U-value, for the STPVs promoting them as good insulators compared with the single glazing case. The south-west facing rooms introduced more savings when it is compared to the south facing rooms. The saving is higher when the transparency is lower. A trade-off can be achieved by using a 40% STPV on the south-west oriented rooms to keep the impact on the mental state at a minimum.

Acknowledgement

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