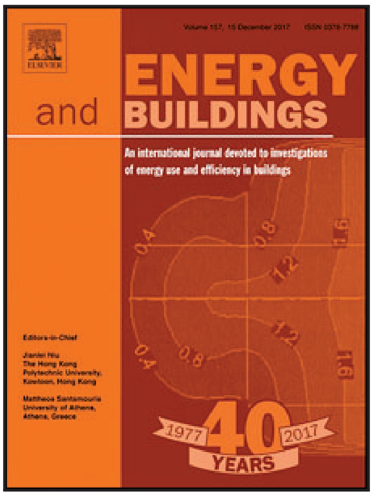
ALRASHIDI, H., ISSA, W., SELLAMI, N., GHOSH, A., MALLICK, T.K. and SUNDARAM, S. 2020. Performance assessment of cadmium telluride-based semi-transparent glazing for power saving in façade buildings. *Energy and buildings* [online], 215, article ID 109585. Available from: https://doi.org/10.1016/j.enbuild.2019.109585.

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

ALRASHIDI, H., ISSA, W., SELLAMI, N., GHOSH, A., MALLICK, T.K., SUNDARAM, S.

2020

Journal Pre-proof



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

Hameed Alrashidi , Walid Issa , Nazmi Sellami , Aritra Ghosh , Tapas. K. Mallick , Senthilarasu Sundaram

PII: S0378-7788(19)30763-7
DOI: https://doi.org/10.1016/j.enbuild.2019.109585
Reference: ENB 109585

To appear in: *Energy & Buildings*

Received date: 19 May 2019
Revised date: 15 October 2019
Accepted date: 4 November 2019

Please cite this article as: Hameed Alrashidi , Walid Issa , Nazmi Sellami , Aritra Ghosh , Tapas. K. Mallick , Senthilarasu Sundaram , Performance Assessment of Cadmium Telluride-based Semi-Transparent Glazing for Power Saving in Façade Buildings, *Energy & Buildings* (2019), doi: https://doi.org/10.1016/j.enbuild.2019.109585

HIGHLIGHTS

- Performance assessment of CdTe-based STPV for saving Façade buildings power
- Calculation, evaluation, and comparison of different glazing and its effect on the air conditioning power and temperatures
- Estimation the lighting energy consumption for different glazing

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

Hameed Alrashidi[1,2] (Corresponding Author)*, Walid Issa[3], Nazmi Sellami[4], Aritra Ghosh[1], Tapas. K. Mallick[1], Senthilarasu Sundaram[1]

[1]Environment and Sustainability Institute, University of Exeter Penryn Campus, Penryn Cornwall, TR10 9FE, UK
[2]Kuwait Fund for Arab Economic Development, Mubarak Al-Kabeer St., Kuwait City, P.O. Box 2921 Safat 13030, Kuwait
[3]Sheffield Hallam University, City Campus, Sheffield, S1 1AA, UK
[4]School of Engineering, Robert Gordon University, Aberdeen, AB10 7JG, UK
* Email Address: Ha314@exeter.ac.uk

Abstract:

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

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

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 [1]. 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 [2]. Windows influence on energy loss from buildings becomes much more drastic when the window area is large like patio doors [3]. Current conventional residential windows are responsible for around 47% of heat loss because of the building fabric [4]. Due to being able to reduce the heat requirement and energy consumption of buildings the significance of windows is given considerable attention for improvement. Li et al. have shown that dispersing nanoparticles in PCM filled windows enhances its optical and thermal performances and leads to an energy saving of 4% [5][6]. In addition, Liu et al. concluded that the optical parameters such as refractive index and extinction coefficients highly affect the optical and thermal performances of a glazing [7].

Recently, Semi-Transparent Photovoltaics (STPV) solar cells have been developed and are popular in research [8]–[14]. 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 [15]. 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 [16].

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 few researchers [17], and it was proven that the use of STPV glazing improves the daylight performance of windows and facades in addition to being promising solution for energy saving to reach a nearly net-zero energy building [18]. Plus, some studies provided a performance assessment of using STPV for a specific location [17], 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. The investigated orientations are South and South West since they are the most favourable for the use of PV cells as they receive the highest solar irradiance in north-hemisphere areas [19]. Also, north orientation is rarely investigated because it receives very little direct solar irradiance [16]. Furthermore, the resultant AC units' power consumption reduction in different scenarios has been assessed and compared with a single glazing.

The main contribution is addressing the practical implementation of CdTe-based STPV on a sample room under the real various surrounding factors. The investigation included the whole picture of thermal conductivity, transparency and orientation to assess its fitness for Façade buildings. In addition, it produces a reference data for simulated models for bigger scaled buildings and bring to attentions few caveats which should be considered in the design and selection.

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

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 in figures 2 and 3. As shown in figure 2, the transmittances of S1, S2, and S3 are 24.83%, 18.66%, and 0.46%, that correspond the visible light range from 380 *nm* – 780 *nm*, which are less than that of the single clear glazing whose transmittance is 90% over the same wavelength range. The provision of the difference transparencies is one of thin-film PVs advantages. These results give STPV the opportunity to be used in different applications such as building facades or office room facades in BIPV, windows, and others.

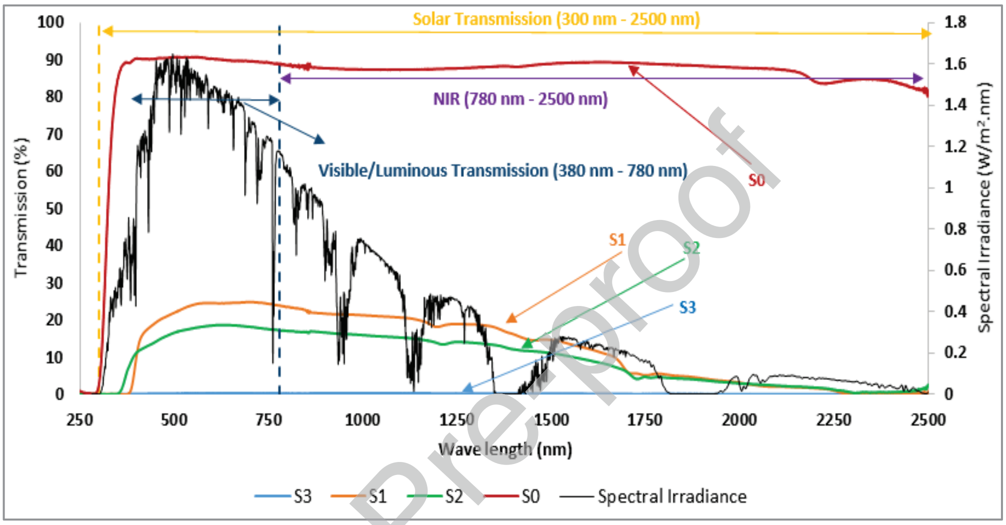


Fig. 2: The Spectral irradiance and transmittance of the STPVs (S1, S2, S3) and the single glazing (S0)

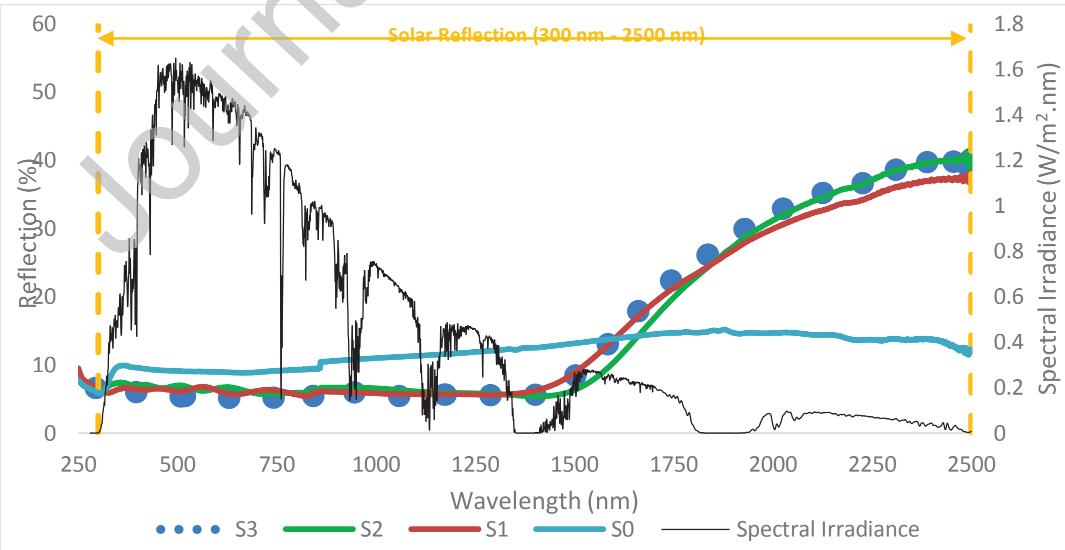


Fig. 3: The spectral irradiance and reflectance of the STPVs and the single glazing

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

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

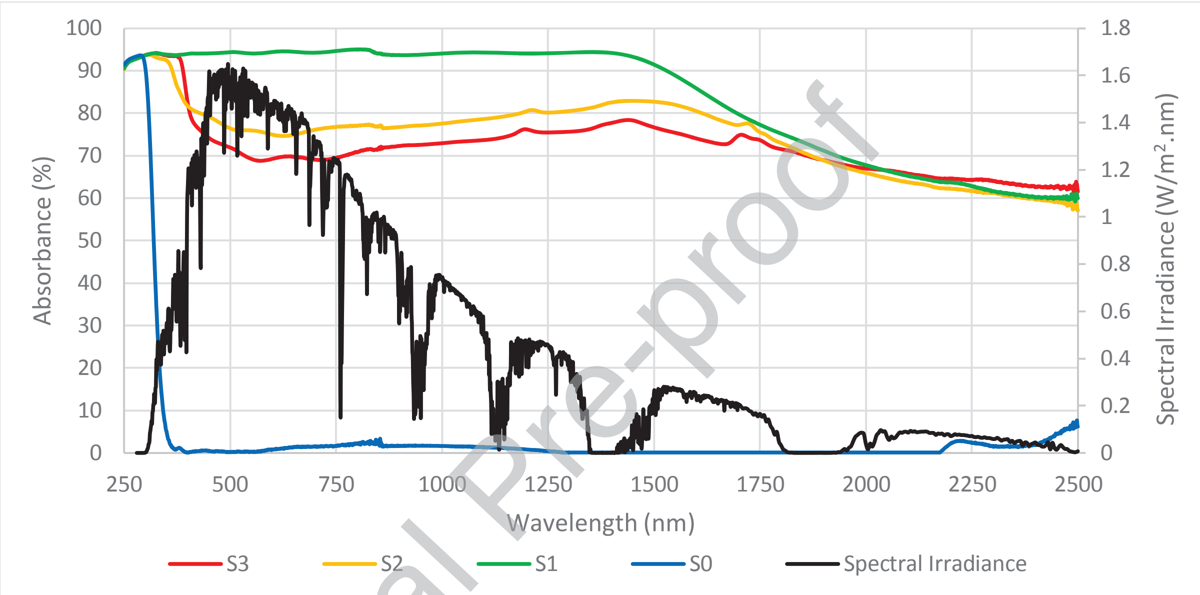


Fig. 4: The spectral irradiance and absorbance of the STPVs and the single glazing

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%

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

The electrical properties of the STPVs were also investigated using WACOM AAA steady state solar simulator. The simulator can provide various levels of continuous irradiances ranging from 300 – 1100 W/m^2. The IV and power 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 table shows slight differences between similar samples in both orientation that can be neglected. 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 were registered for S3 whereas S1 showed the lowest efficiency and power generation.

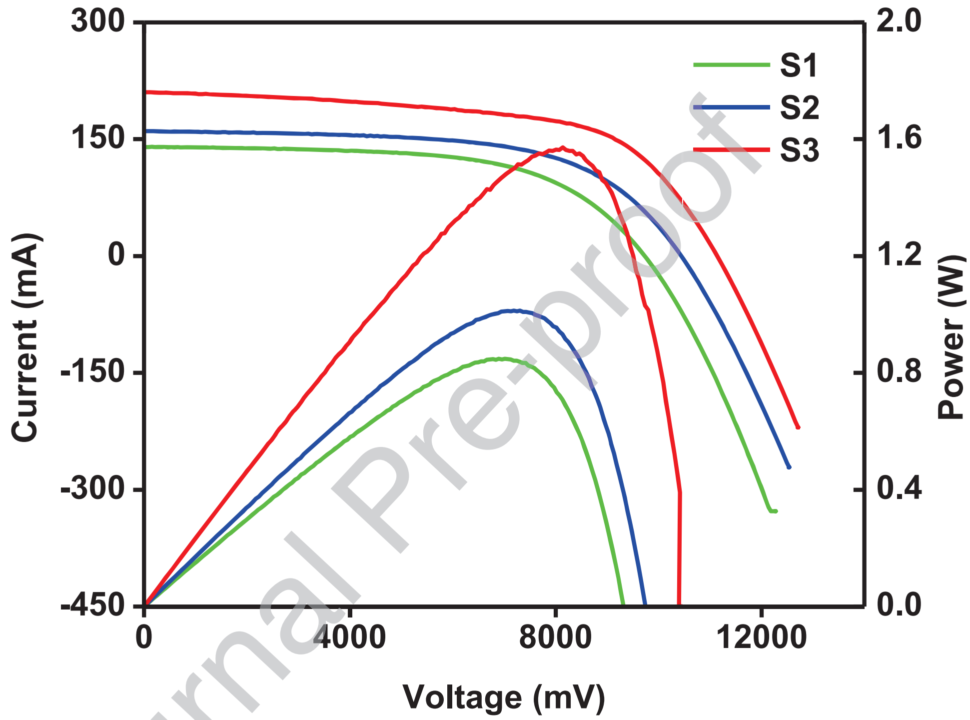


Fig. 5: The IV and power curves of STPVs used in south-west-oriented test cell

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	0.812
Short Circuit Current [Isc] (A)	0.22	0.16	0.14	0.21	0.16	0.13
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	0.112
Voltage at Maximum Power Point [Vmp] (V)	8.49	7.57	7.05	8.65	7.43	7.11
Efficiency [η] (%)	12.6	8.23	6.7	11.69	8.15	6.6

3. Methodology

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

The design had two identical sets of four rooms set to the south and south-west directions. Because of the constraint of a fixed size of the available STPV (20 X 20 cm^2) the rooms had been designed with dimensions of 20 X 20 cm^2. It is worth mentioning that the active area of the STPV is within the 10 X 10 cm^2. The use of small scale test rooms was demonstrated to be efficient in different studies as they reflect the real behaviour of the glazing in outdoor conditions when exposed to real weather conditions for long periods of time [20][21][22].

Each room had insulated sides made of polystyrene sheets (thickness of 2.5 cm) to provide good insulation so that we could neglect any side thermal disturbances except for one side, which represented the window. The rooms utilized Peltier-based cooling systems for mimicking the AC units in the buildings. Also, each room was equipped with:

- K-type temperature sensors of accuracy ±0.5 ^{o}C, outer and inner cell surfaces inside the room for thermal evaluation
- a GmbH, D-78467 light sensor in the middle of the room
- Arduino ADC based-voltage sensor and ACS712 current sensors for AC power consumption measurements
- NI voltage sensor for the STPV power generation measurement

In addition, a pyranometer and pyrheliometer were used to measure the global, direct and diffuse solar irradiances.

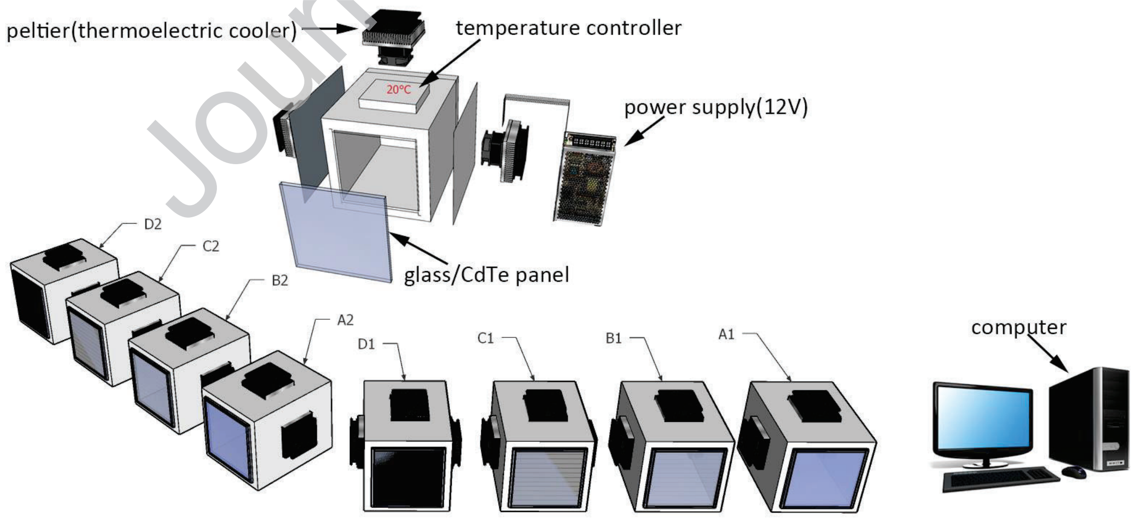


Fig. 6: The schematic diagram of the experimental setup.

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

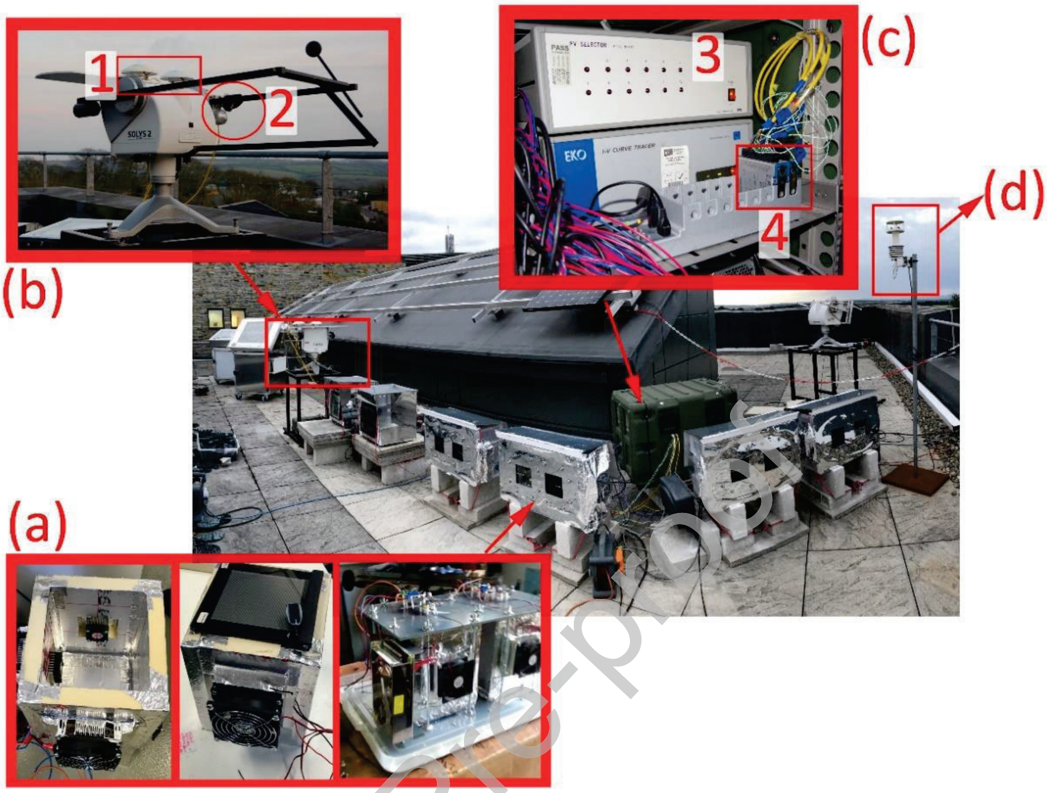


Fig. 7: The Completed view of the whole setup: (a) test cell (b) solar tracker (1) global and diffuse radiation (2) the direct radiation (c) data logger (3) IV-tracer (4) thermocouple data logger (d) weather station

The indoor experiments were carried out on each room by thermal performance evaluations and for AC power consumption assessments under various irradiances of solar simulator with different glazing 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 thermal performances of the tested glazing were evaluated by U-value and SHGC. The measured solar irradiances and temperature were used to calculate the U-values through the following equation [23]:

$$Q_{in} = Q_g + Q_{tc} + Q_{loss} + P \tag{1}$$

where; Q_{in} is the total heat incident on the glazing, Q_g is the heat transmitted through the glazing, Q_{tc} is the heat stored inside the test rooms, Q_{loss} is the heat loss through the surface of the glazing and P is the power generation of the STPV glazing. All units are in (W)

Whereas the SHGC was calculated through the following equation [24]:

$$SHGC = {}^{TSE}/_{I_{ver,global}} \tag{2}$$

Where; TSE is the transmitted solar energy through the glazing in (W/m^2) and $I_{ver,global}$ is the global vertical irradiance (W/m^2)

The U-values and SHGC of the tested glazing are presented in Table 3 below. In the results, S0 has the highest U-value among all the tested cells, then the other cells can be arranged in descending order of U-value as S1, S2, and finally S3. This pattern is applicable for both the south and south-west orientations. It is noticed that glazing with lower transparency have higher U-values, this is because of the denser CdTe thin-film layer that increases the heat resistance of the glazing. As for the SHGC, S0 was shown to have the highest value in both orientations. The other glazings of SHGC can be arranged again in descending order as S1, S2, and S3. Nevertheless, table 3 demonstrates the effects of orientation on the insulation properties of the glazing.

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
S0	5.67 W/m^{2}K	5.6 W/m^{2}K	0.728	0.713
S1	2.64 W/m^{2}K	2.7 W/m^{2}K	0.202	0.198
S2	2.35 W/m^{2}K	2.3 W/m^{2}K	0.145	0.142
S3	1.54 W/m^{2}K	1.52 W/m^{2}K	0.029	0.028

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

5. Room temperature and Air conditioning

As per Lomas and Kane [25], the range of comfort temperature in winter and summer seasons is below 24°C. Also according to Seppanen, Fisk, and Lei [26], the performances increase with temperatures up to 22°C and decreases with temperatures above 24°C. In this trial, the thermostat was set at 20°C for cooling to calculate the AC loads. According to the UK weather, keeping the inside temperature of the room below 20°C is not hard. However, in hot countries, i.e. in the Middle East, it needs the AC to work for a longer time with higher capacity to achieve the 20°C regulation.

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

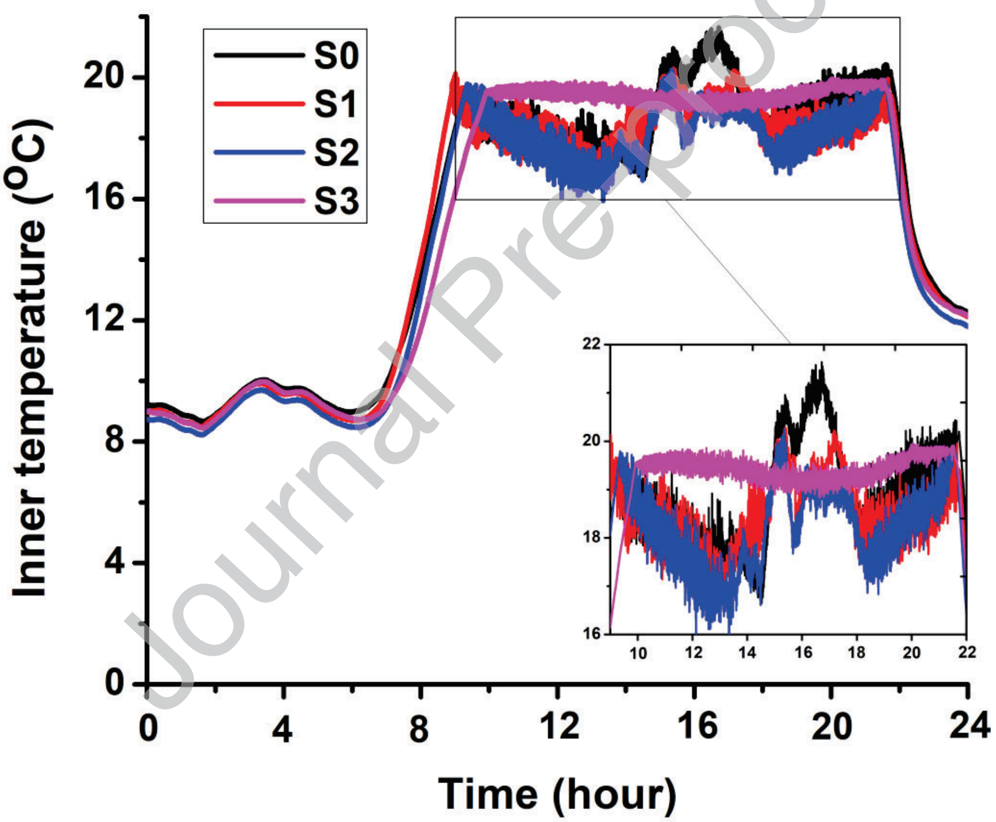


Fig. 8: The inner-temperature profiles of the south-facing rooms on 6 May 2018

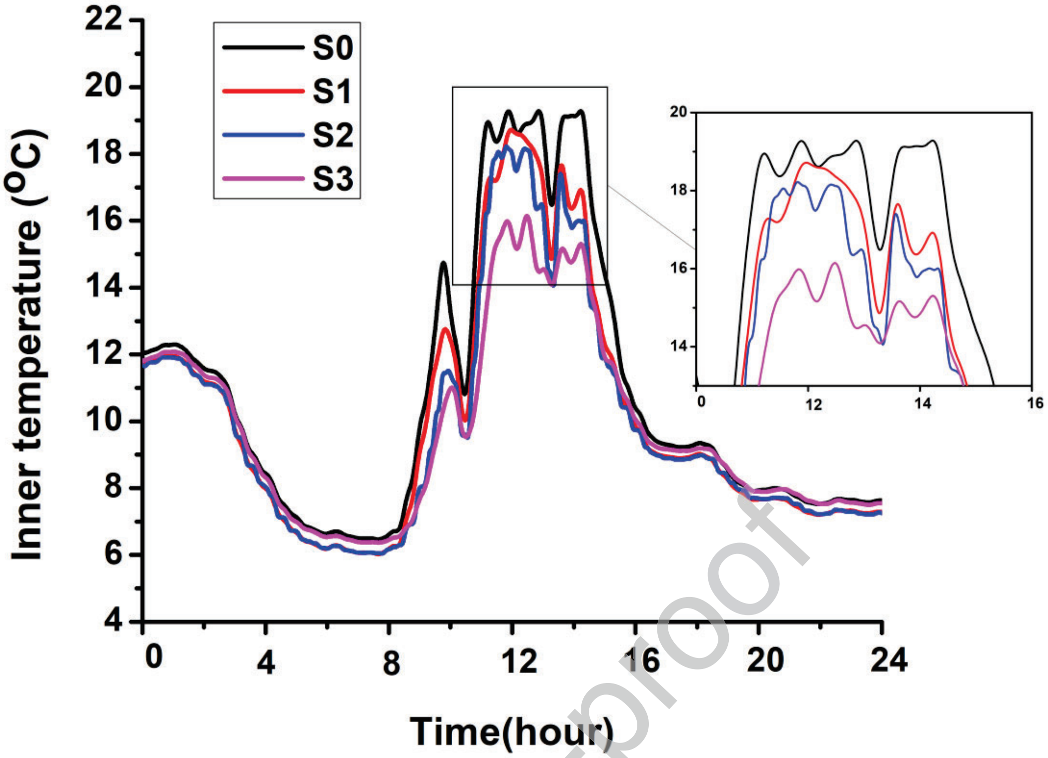


Fig. 9: The inner-temperature profiles of the south-facing rooms on 23 November 2017

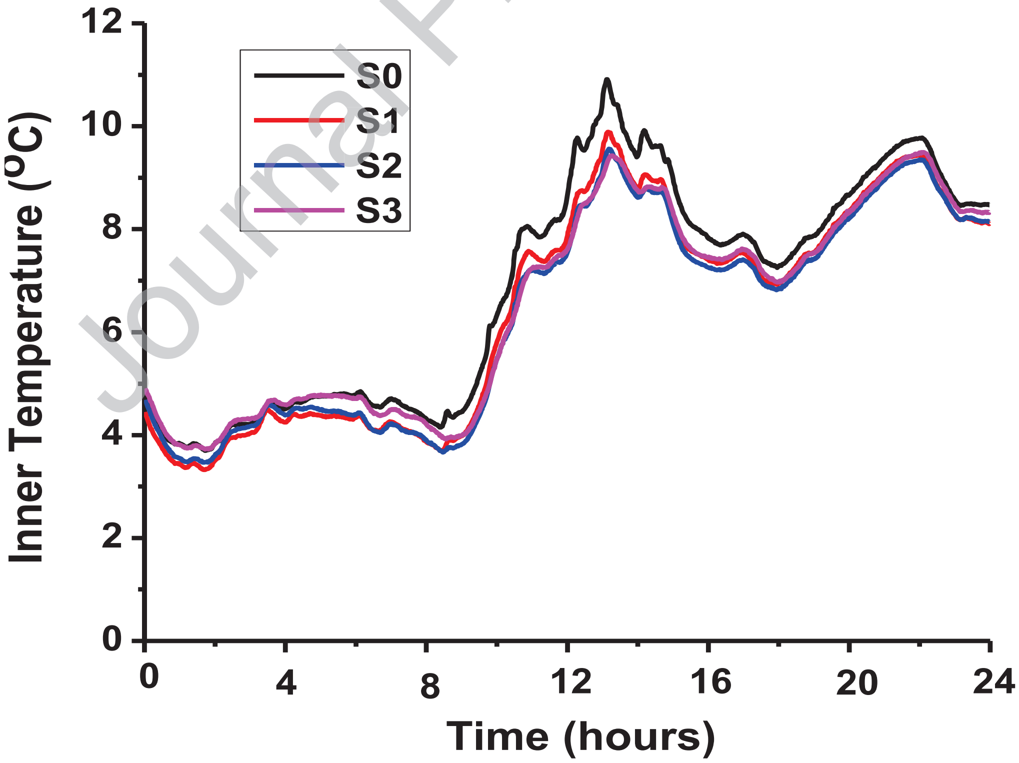


Fig. 10: The inner-temperature profiles of the south-facing rooms on 12 December 2017

6. Results and discussion

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. Figure 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.

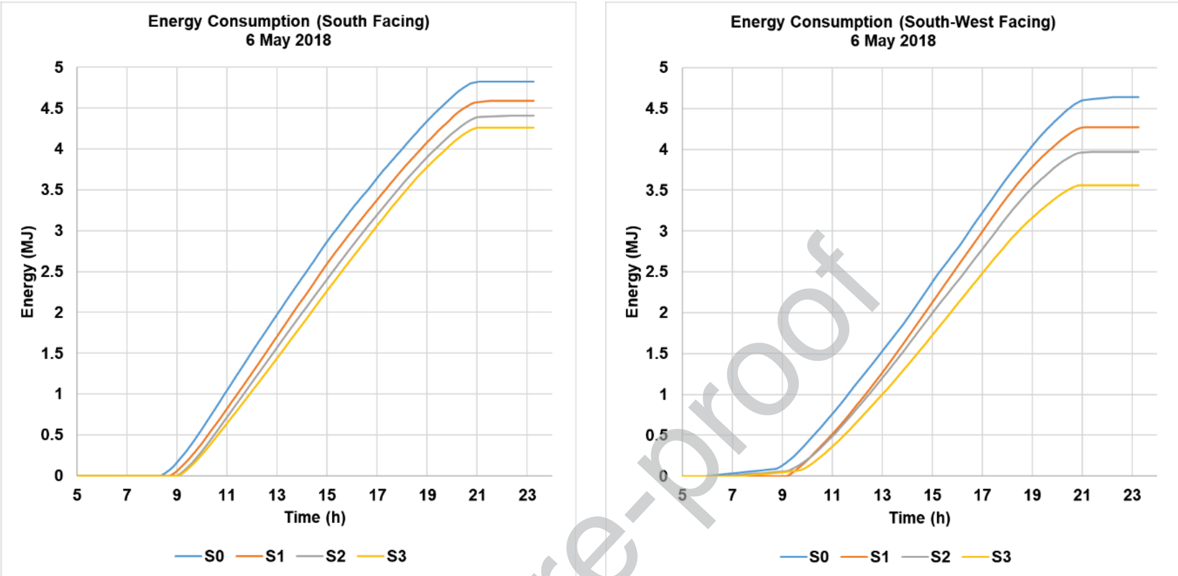


Fig. 11: The AC energy consumption for different orientations and different transparencies on 6 May 2018

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.

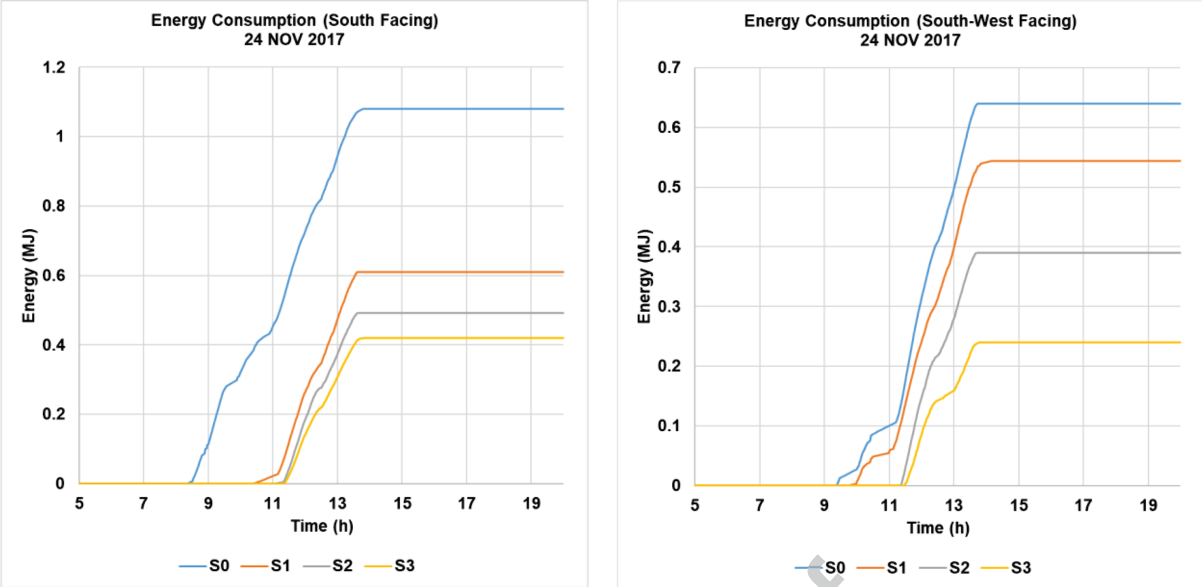


Fig. 12: The AC energy consumption for different orientations and different transparencies on 24 Nov 2017

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.

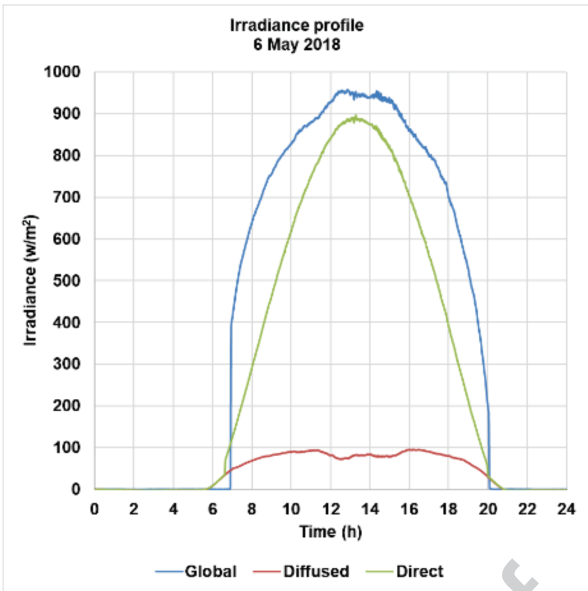


Fig. 13: The direct, diffused, and global irradiance on 6 May 2018

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 [8].

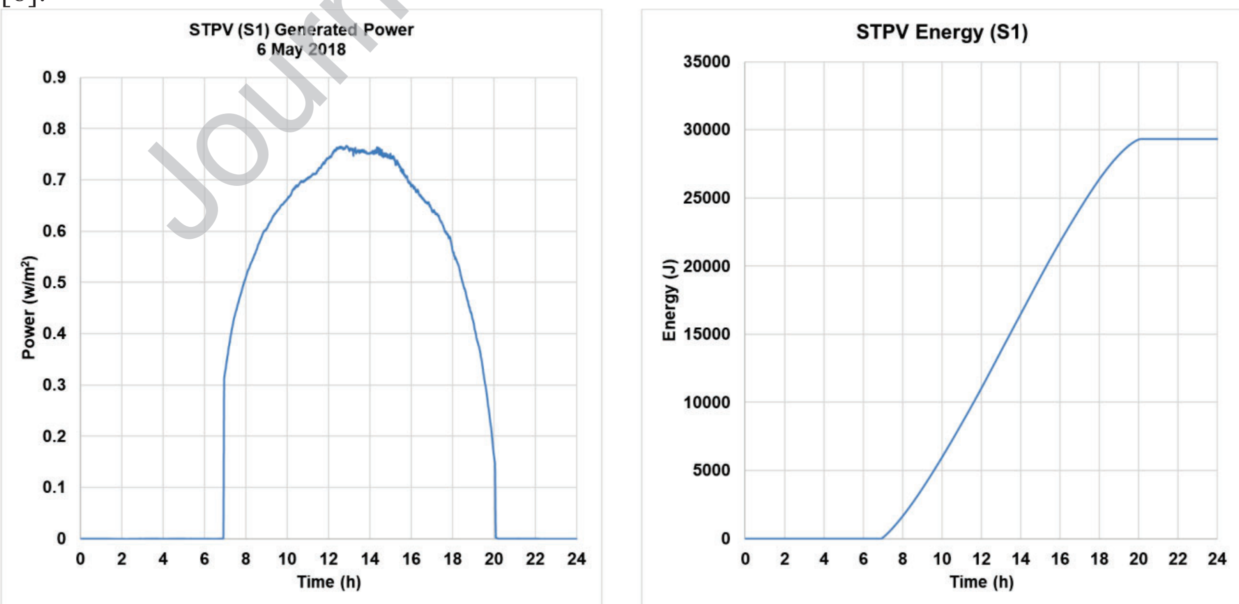


Fig. 14: The generated power and energy of the S1 STPV room

6.3. Interior lighting compensation

In UK standards, the lighting requirement for a façade building for offices is about 500 lumen/m^2 [27]. This can be translated into 9 – 13 W/m^2 if tubular fluorescent lighting is used [28]. For twelve hours (7 am to 7 pm) a 10 W/m^2 had been chosen as the average required value. With an artificial lighting dimming control system introduced the artificial lighting will be activated and reach the required illuminance level, with the extra electricity consumption calculated when the daylight illuminance level is below 500 Lux.

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

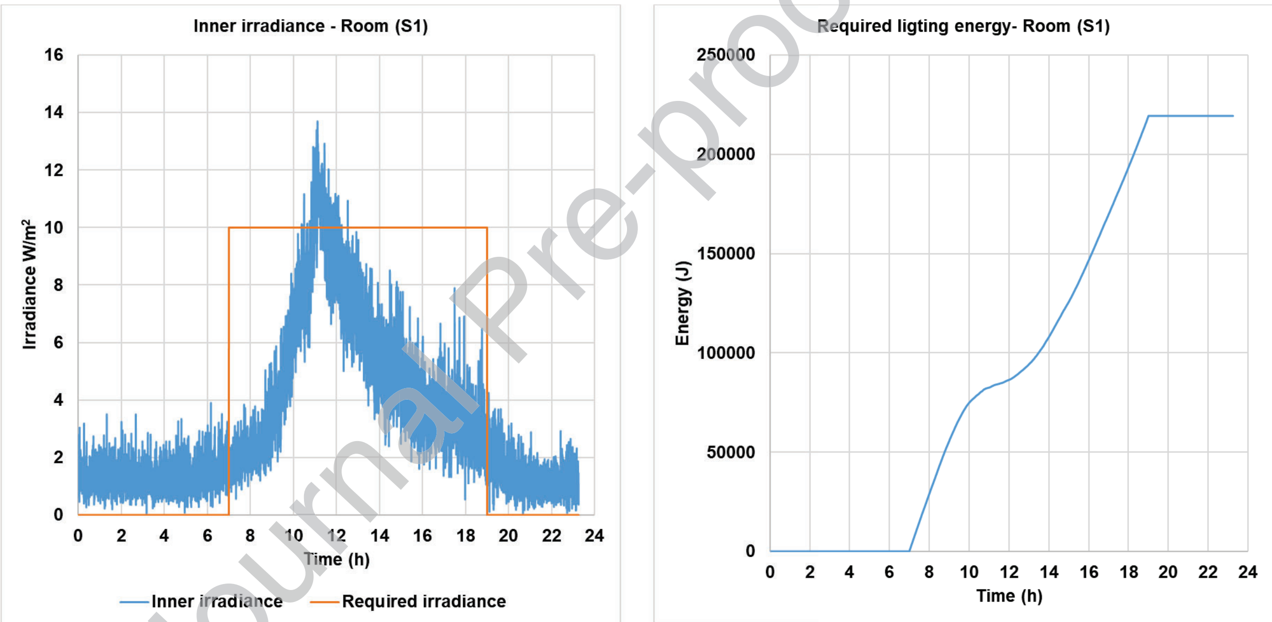


Fig. 15: The inner irradiance of the room (S1) and the required lighting energy

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.

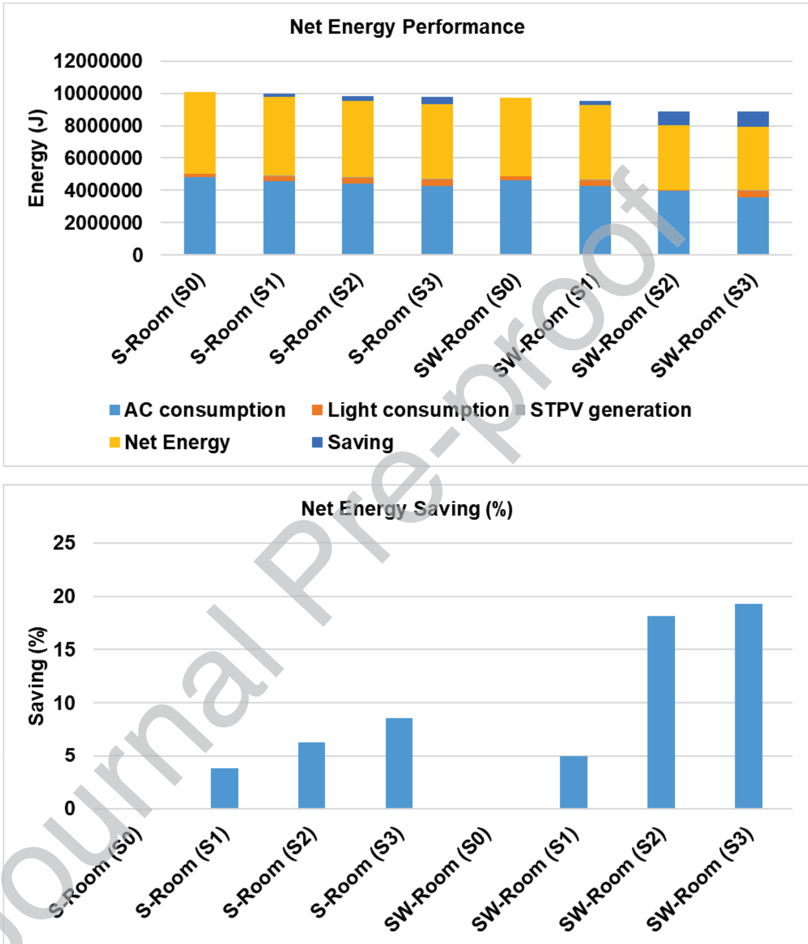


Fig. 16: Net generation performance

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 [29]. 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 4.

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. It is concluded that the transparency of the STPV samples in the study correlate with the U-value. Less transparent PV provides higher insulation, U-value from 1.52 to 2.7 W/m^{2}K. This supports the proposal of using STPV in Façade building where more heat can be reflected, and less cooling power is consumed. However, low transparency required more artificial lighting. The experimental results of the power consumption for the south and south-west orientation shown that the south-west provide better performance for all sample transparencies. The net energy savings starts from 5% for 40% transparency to about 20% for 10% transparency. However, to consider the friendly environment and health sides for the residents, 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

This work is funded through PhD fellowship by Kuwait Fund for Development is greatly acknowledged.

Conflict of Interest

The authors declare that there is no conflict of interest

References

[1] "International Energy Agency, World Energy Statistics and Balances 2017."

[2] G. Baldinelli *et al.*, "Energy and environmental performance optimization of a wooden window: A holistic approach," *Energy Build.*, vol. 79, pp. 114–131, Aug. 2014.

[3] E. Cuce, C. H. Young, and S. B. Riffat, "Performance investigation of heat insulation solar glass for low-carbon buildings," *Energy Convers. Manag.*, vol. 88, pp. 834–841, Dec. 2014.

[4] E. Cuce, C. H. Young, and S. B. Riffat, "Thermal performance investigation of heat insulation solar glass: A comparative experimental study," *Energy Build.*, vol. 86, pp. 595–600, Jan. 2015.

[5] D. Li, Y. Wu, C. Liu, G. Zhang, and M. Arıcı, "Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM," *Int. J. Heat Mass Transf.*, vol. 125, pp. 1321–1332, Oct. 2018.

[6] D. Li, Y. Wu, C. Liu, G. Zhang, and M. Arıcı, "Energy investigation of glazed windows containing Nano-PCM in different seasons," *Energy Convers. Manag.*, vol. 172, pp. 119–128, Sep. 2018.

[7] C. Liu, J. Bian, G. Zhang, D. Li, and X. Liu, "Influence of optical parameters on thermal and optical performance of multi-layer glazed roof filled with PCM," *Appl. Therm. Eng.*, vol. 134, pp. 615–625, Apr. 2018.

[8] J. Peng, D. C. Curcija, L. Lu, S. E. Selkowitz, H. Yang, and W. Zhang, "Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate," *Appl. Energy*, vol. 165, pp. 345–356, Mar. 2016.

[9] F. Chen, S. K. Wittkopf, P. Khai Ng, and H. Du, "Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator," *Energy Build.*, vol. 53, pp. 74–84, Oct. 2012.

[10] T. Y. Y. Fung and H. Yang, "Study on thermal performance of semi-transparent building-integrated photovoltaic glazings," *Energy Build.*, vol. 40, no. 3, pp. 341–350, Jan. 2008.

[11] T. Miyazaki, A. Akisawa, and T. Kashiwagi, "Energy savings of office buildings by the use of semi-transparent solar cells for windows," *Renew. Energy*, vol. 30, no. 3, pp. 281–304, Mar. 2005.

[12] L. Olivieri, F. Frontini, C. Polo-López, D. Pahud, and E. Caamaño-Martín, "G-value indoor characterization of semi-transparent photovoltaic elements for building integration: New equipment and methodology," *Energy Build.*, vol. 101, pp. 84–94, Aug. 2015.

[13] J. H. Yoon, J. Song, and S. J. Lee, "Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module," *Sol. Energy*, vol. 85, no. 5, pp. 723–733, May 2011.

[14] G. Y. Yun, M. McEvoy, and K. Steemers, "Design and overall energy performance of a ventilated photovoltaic façade," *Sol. Energy*, vol. 81, no. 3, pp. 383–394, Mar. 2007.

[15] C. Catita, P. Redweik, J. Pereira, and M. C. Brito, "Extending solar potential analysis in buildings to vertical facades," *Comput. Geosci.*, vol. 66, pp. 1–12, May 2014.

[16] S. Barman, A. Chowdhury, S. Mathur, and J. Mathur, "Assessment of the efficiency of window integrated CdTe based semi-transparent photovoltaic module," *Sustain. Cities Soc.*, vol. 37, pp. 250–262, Feb. 2018.

[17] V. Sharma and S. S. Chandel, "Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review," *Renew. Sustain. Energy Rev.*, vol. 27, pp. 753–767, Nov. 2013.

[18] S. Mende, F. Frontini, and J. Wienold, "(PDF) Comfort and building performance analysis of transparent building integrated silicon photovoltaics," in *12th Conference of International Building Performance Simulation Association*, 2011.

[19] S. B. Sadineni, F. Atallah, and R. F. Boehm, "Impact of roof integrated PV orientation on the residential electricity peak demand," *Appl. Energy*, vol. 92, pp. 204–210, Apr. 2012.

[20] D. P. Grimmer, R. D. McFarland, and J. D. Balcomb, "Initial experimental tests on the use of small passive-solar test-boxes to model the thermal performance of passively solar-heated building designs," *Sol. Energy*, vol. 22, no. 4, pp. 351–354, Jan. 1979.

[21] H. Manz, P. Loutzenhiser, T. Frank, P. A. Strachan, R. Bundi, and G. Maxwell, "Series of experiments for empirical validation of solar gain modeling in building energy simulation codes-Experimental setup, test cell characterization, specifications and uncertainty analysis," *Build. Environ.*, vol. 41, no. 12, pp. 1784–1797, Dec. 2006.

[22] G. Alvarez, M. Jimenez, and M. Heras, "Preliminary study of small scale solar test cells for solar thermal evaluation of building components," in *EuroSun 2004-14*, 2004.

[23] A. Ghosh, B. Norton, and A. Duffy, "Measured overall heat transfer coefficient of a suspended particle device switchable glazing," *Appl. Energy*, vol. 159, pp. 362–369, Dec. 2015.

[24] A. Ghosh, B. Norton, and A. Duffy, "Measured thermal & daylight performance of an evacuated glazing using an outdoor test cell," *Appl. Energy*, vol. 177, no. 169, pp. 196–203, 2016.

[25] K. J. Lomas and T. Kane, "Summertime temperatures and thermal comfort in UK homes," *Build. Res. Inf.*, vol. 41, no. 3, pp. 259–280, Jun. 2013.

[26] O. Seppanen, W. J. Fisk, and Q. H. Lei, "Effect of Temperature on Task Performance," *Lawrence Berkeley Natl. Lab.*, 2006.

[27] CIBSE, *CIBSE Guide A: Environmental Design*, vol. 30. 2015.

[28] D. Jenkins and M. Newborough, "An approach for estimating the carbon emissions associated with office lighting with a daylight contribution," *Appl. Energy*, vol. 84, no. 6, pp. 608–622, Jun. 2007.

[29] M. B. C. Aries, J. A. Veitch, and G. R. Newsham, "Windows, view, and office characteristics predict physical and psychological discomfort," *J. Environ. Psychol.*, vol. 30, no. 4, pp. 533–541, Dec. 2010.