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MUSAMEH, Haytham, AL-NAEMI, Faris, ISSA, Walid <http://orcid.org/0000-0001-9450-5197> and ALRASHIDI, Hameed

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The Thermal and Optical Characterization of Semi-transparent Photovoltaics Samples for Buildings Energy Evaluations

Haytham Musameh
Faris Al-naemi
Walid Issa
Sheffiled Hallam University
Sheffield, UK
Hom493@hallam.shu.ac.uk

Hameed Alrashidi
Environment and Sustainability Institute
University of Exeter
Penryn, UK
basicolor@hotmail.com

***Abstract*— Using Semi-transparent PV (STPV) as glazing in buildings might improve the building's energy profile. However, the characterization method has to be identified. This work aims to establish the experimental methodology utilized in characterizing various glazing SPTV samples and draw its potential impact on buildings. The results indicate that STPV-based CdTe solar cells tend to reduce the amount of natural light that can enter the indoor environment, therefore, increasing the lighting demands and reducing the passive heating element, which would increase the heating demand. Furthermore, it minimizes the heat gain caused by solar radiation passing through the glazing. This suggests that CdTe STPV glazing samples can serve as effective shading devices, ultimately reducing the cooling requirements of buildings. Finally, the CdTe STPV glazing systems exhibit better insulation properties compared to conventional single and double-glazing samples, regardless of their structure.**

Keywords*— *STPV, building energy, CdTe

I. Introduction

As the global population continues to grow, the need for energy sources, particularly electricity, is on the rise. This demand is largely driven by the building sector, which accounts for approximately 20% of the world's economy. However, the building sector is faced with a myriad of challenges related to energy supply, resources, the environment, and climate change. As a result, there is a growing movement to lower energy consumption levels and shift towards renewable energy sources. Recent studies have shown that the building sector consumes roughly 30% of the world's electricity, primarily to meet the heating and cooling requirements. In the United States, for example, 61% of the energy consumed in commercial buildings is attributed to the heating and cooling demands of glazing systems. In 2010, the building sector was responsible for utilizing more than 40% of the energy generated in the US, with approximately 50% of it directed towards meeting the heating and cooling requirements [1]-[5].

In order to tackle the energy consumption issues, it is imperative to conduct a thorough analysis of the underlying sources and factors. After extensive research, glazing systems have been identified as a crucial area that requires improvement. These systems play a pivotal role in regulating heat transfer within the building's structure, thus exerting a significant influence on its overall thermal performance [4], [6].

The demand for photovoltaic technologies has been on the rise, mainly because of their adaptability. Their remarkable flexibility makes them an ideal option for urban areas and cities, where they can be fitted onto building roofs or even integrated into the building structure.

Integrating solar cells into glazing systems presents a potential solution for decreasing overall energy consumption in buildings. However, before implementing such technology, several crucial factors must be taken into account, such as the climate profile of the location and the surrounding structures that may cast shadows. The integration of solar cells not only produces electricity but also enhances the building's thermal performance, rendering semi-transparent photovoltaic (STPV) glazing systems a highly appealing option.

It is crucial to conduct a thorough analysis and evaluation when planning to utilize STPV glazing systems in a building. These systems incorporate solar cells that regulate the amount of solar radiation that penetrates the building, thereby reducing the amount of natural daylight and outdoor views. This, in turn, can have a significant impact on the lighting demand and thermal performance of the building's interior. Therefore, careful consideration and appropriate design adjustments must be made to ensure optimal outcomes [7], [8].

The objective of this work is to establish the experimental methodology utilized in characterizing various glazing samples examined in this research. The characterization process will delve into the physical properties of the samples used in the study and provide details on the experimental setup employed to obtain the different properties of these samples.

Table I
Glazing Samples

Sample	Sample type	Solar cells materials
S1	STPV	CdTe
S3	Double glazing STPV	CdTe
DG1	Double glazing	N/A
SG1	Single glazing	N/A

II. METHODOLOGY

A. Glazing samples

Various samples of CdTe STPV glazing, a clear double-glazing sample, and one clear single-glazing sample, were utilized. Table I shows the glazing samples that are being tested in this paper.

B. Indoor experimental set-up

To evaluate the impact of CdTe STPV glazing systems on energy efficiency, a series of experimental tests were performed to determine their key attributes. These tests took place in a controlled environment, utilizing the Guarded Hot Box technology designed by Fung et al. [9] and the Mobile Window Thermal Test (MoWiTT) developed by Robinson and Littler [10].

1) *Guarded Hot Box and Mobile Window Thermal Test*

A guarded hot box is an experimental setup designed for the calculation of U-values of specific samples. This setup comprises three distinct compartments: the guard box, the metering box, and the sample under investigation, which is positioned between the cold box and the metering box. The cold box is responsible for regulating low temperatures to simulate the cooling system in use, while the guard box functions as a temperature controller to prevent heat loss and maintain optimal conditions. The metering box features a heater that facilitates the transfer of heat from the metering box to the cold box through the sample under examination [9] *as shown in* Fig. 1.

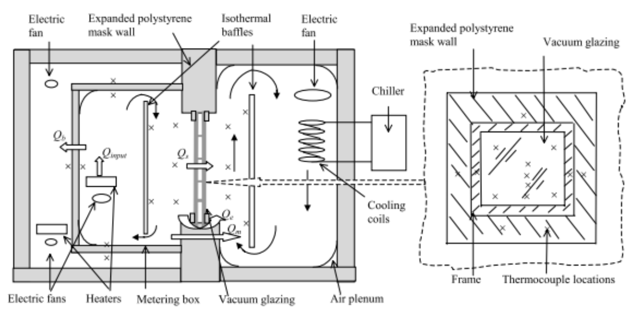

Fig. 1. Guarded Hot Box [9].

The Mobile Window Thermal Test (MoWiTT) is an experimental setup designed to measure the U-value, much like the Guarded Hot Box. However, MoWiTT offers the added benefit of examining how the surrounding environment affects the tested sample's thermal performance.

2) *Enclosure testbed setup and Attributes*

Experimental tests conducted within enclosed spaces often require a controlled indoor temperature. To achieve this, heating and/or cooling systems are managed within the testbed setup. In order to collect essential data required for creating electrical, thermal, and optimal profiles for various CdTe STPV samples, a testbed was constructed. The tests were conducted in a controlled environment at the power and transmission lab in Sheaf Building, Sheffield Hallam University, Sheffield, United Kingdom. Standard testing conditions (STC) were maintained throughout the experiments, including an ambient temperature of 25°C, air mass of 1.5, wind speed of 1 m/s, and solar irradiance of 1000 W/m². The building's central heating system was utilized to regulate the temperature, while a mechanical ventilation system was used to control air mass and wind speed. Furthermore, to ensure consistent irradiance, a solar simulator was developed. The enclosure consisted of thermo-electric coolers (Peltier unit) that were used to maintain ambient temperature. The enclosure testbed structure is made of insulated Polyisocyanurate and laminated with aluminium foil for temperature control. It measures 0.3m x 0.3m x 0.225m, with minimal thermal disturbances, as shown in Fig. 2. The used testbed includes three pelters units and two thermo-couplers for accurate and reliable testing.

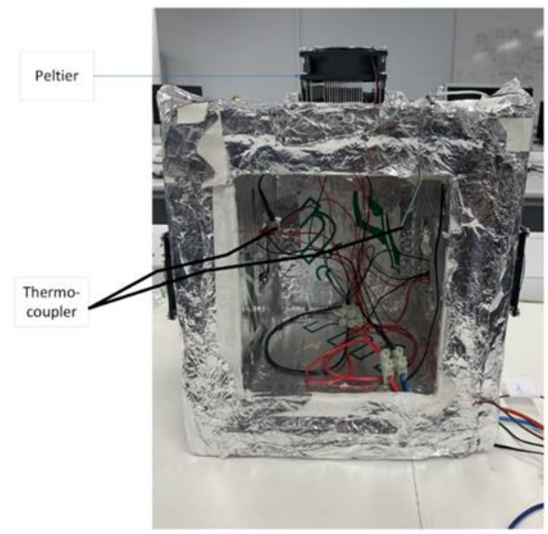

Fig. 2. The Developed Enclosure Testbed

3) *Optical Characterisation Testing Setup*

When evaluating the optical characteristics of a glazing sample, the interaction with solar irradiance is a key factor. A transparent sample can allow solar irradiance to penetrate the indoor environment while absorbing some of it. The fenestration of the sample can also reflect a percentage of the solar irradiance. It's essential to take into account the glazing sample's transmittance, absorbance, and reflectance since these three attributes can significantly affect its performance. According to (1), the sum of these three attributes is equal to unity.

$$\rho(\lambda,\theta) + \tau(\lambda,\theta) + \alpha(\lambda,\theta) = 1 \quad (1)$$

Where:
ρ: The reflected solar irradiance (unitless).
τ: The Transmitted solar irradiance (unitless).
α: The absorbed solar irradiance (unitless).
λ: The spectrum of the solar irradiance (nm).
θ: The incident angle of the solar irradiance (degree).

The acquisition of data was performed using a spectrometer from Avantes (Avaspec-ULS-EVO-RS) model, which is capable of covering the wavelength range from 200-1100 nm.

In conjunction with this, a Lightsource (Avalight-DHc) was utilized, providing both deuterium and halogen light sources with a wavelength range of 200-2500 nm. To record the results, the Avasoft software was utilized. The optical characterization testing setup can be seen in Fig. 3, while Fig. 4 displays the SG1 sample being tested at a 0° angle. Each sample has been subjected to multiple iterations of the optical testing under different incident angles, specifically from 0° to 40° due to the testing setup limitation.

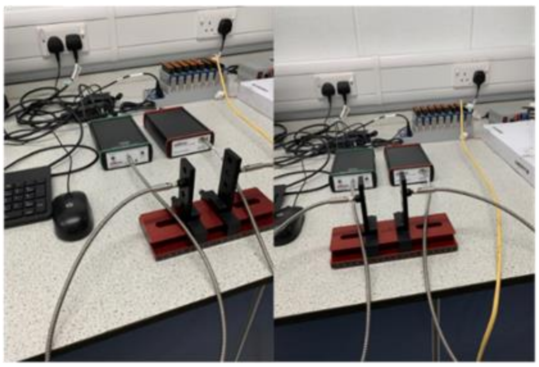

Fig. 3. Spectrometer (Avaspec-ULS-EVO-RS) along with a Lightsource (Avalight-DHc)

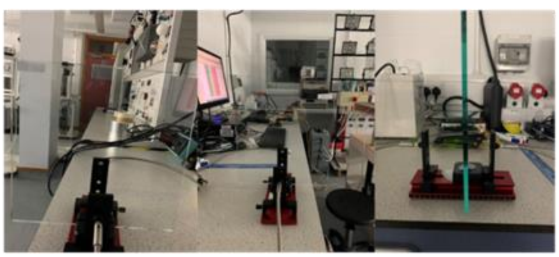

Fig. 4. The optical Characterisation testing for SG1 at 0°

1) *Thermal Characterisation Testing Setup*

The Thermal Characterisation Testing Setup aims to assess the thermal properties of CdTe STPV glazing samples through the U-value and SHGC metrics.

a) SHGC Characterisation Testing Setup

The SHGC metric is determined by the optical properties of CdTe STPV glazing systems, specifically the levels of solar irradiance that are transmitted and absorbed [14]. Additionally, SHGC is a metric that measures the amount of solar irradiance that enters the indoor environment through the glazing system. It also measures the solar heat gain through the glazing structure.[15]. SHGC can be calculated according to equation (2) [16].

$$\mathrm{SHGC}(\lambda,\theta) = \tau(\lambda,\theta) + \mathrm{N} * \alpha(\lambda,\theta) \quad (2)$$

Where:
τ: The Transmitted solar irradiance (unitless).
α: The absorbed solar irradiance (unitless).
λ: The spectrum of the solar irradiance (nm).
θ: The incident angle of the solar irradiance (degree).
$SHGC$: The Solar Heat Gain Coefficient (unitless).
N: The inward-flowing fraction of the absorbed radiation (unitless).

The inward-flowing fraction of the absorbed radiation (N) is a unitless ratio between the U-value and the external heat transfer, were both measured in (W/m^2), $N = U/h_e$ [17].

a) U-value Characterisation Testing Setup

The U-value is used to measure the energy transmitted through the glazing system by considering both the exchange of irradiation and convective heat between the inner and outer surfaces of the glazing [18]. The heat transfer coefficient is determined by the heat flux (W/m2) and the temperature difference between the inner and outer surfaces of the glazing system (Kelvin). This can be calculated using an equation (3) below [19]-[21].

$$U = Q/\Delta T \quad (3)$$

Where:
U: the heat transfer coefficient (W/m^2.K)
Q: The heat flux (W/m^2)
ΔT: The temperature difference between the glazing system's inner and outer surface (Kelvin).

To determine the U-value of various glazing samples, it is necessary to measure the heat flux value and the inner and outer surface temperatures. The g-SKIN U-VALUE KIT 2615C from greenTEG is a specialized kit that includes a heat flux sensor, two thermocouple sensors, and a data logger shown in Fig. 5 to obtain these values. The data collected from the experiments are then analysed using the greenTEG Logger 1.02.10 software.

Fig. 5. g-SKIN U-VALUE KIT 2615C

In the experiment, the U-Value metric for various glazing samples was measured using the practical setup depicted in Fig. 6. It's important to note that Peltier units were employed to raise the ambient temperature of the testbed enclosure above the lab ambient temperature. This facilitated heat flux from indoor to outdoor environments through the glazing sample, similar to Fang et al. [9] work.

III. Result and Discussion

A. The Optical Characteristics

The optical test results are shown in Fig. 7 and Fig. 8, and the average values are shown in Table II. The results indicate that CdTe solar cells tend to reduce the amount of natural light that can enter the indoor environment. Integrating the CdTe STPV glazing systems into buildings would increase the lighting demands and reduce the passive heating element, which would increase the heating demand.

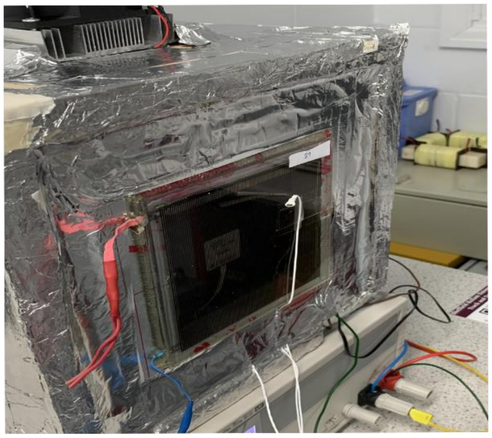

Fig. 6. The Practical Setup of U-Value Measurement

TABLE II
THE AVERAGE VALUES FOR THE OPTICAL TEST

Sample	Transmittance%	Absorbance%	Reflectance%
S1	26.24	6.23	67.53
S3	23.20	5.64	71.16
DG1	69.83	14.97	15.20
SG1	74.00	15.81	10.19

TABLE III
THE SHGC AVERAGE VALUES

Sample	SHGC
DG1	0.91
SG1	0.92
S1	0.36
S3	0.32

B. The Thermal Characteristics

1) SHGC Results

As stated in the methodology the SHGC metric is dependent on the optical characteristics of the glazing samples according to equation (2).

The findings indicate that CdTe STPV glazing systems minimize heat gain caused by solar radiation passing through the glazing. This suggests that CdTe STPV glazing samples can serve as effective shading devices, ultimately reducing the cooling requirements of buildings. The results are shown in Fig. 9, and the average values are shown in Table III.

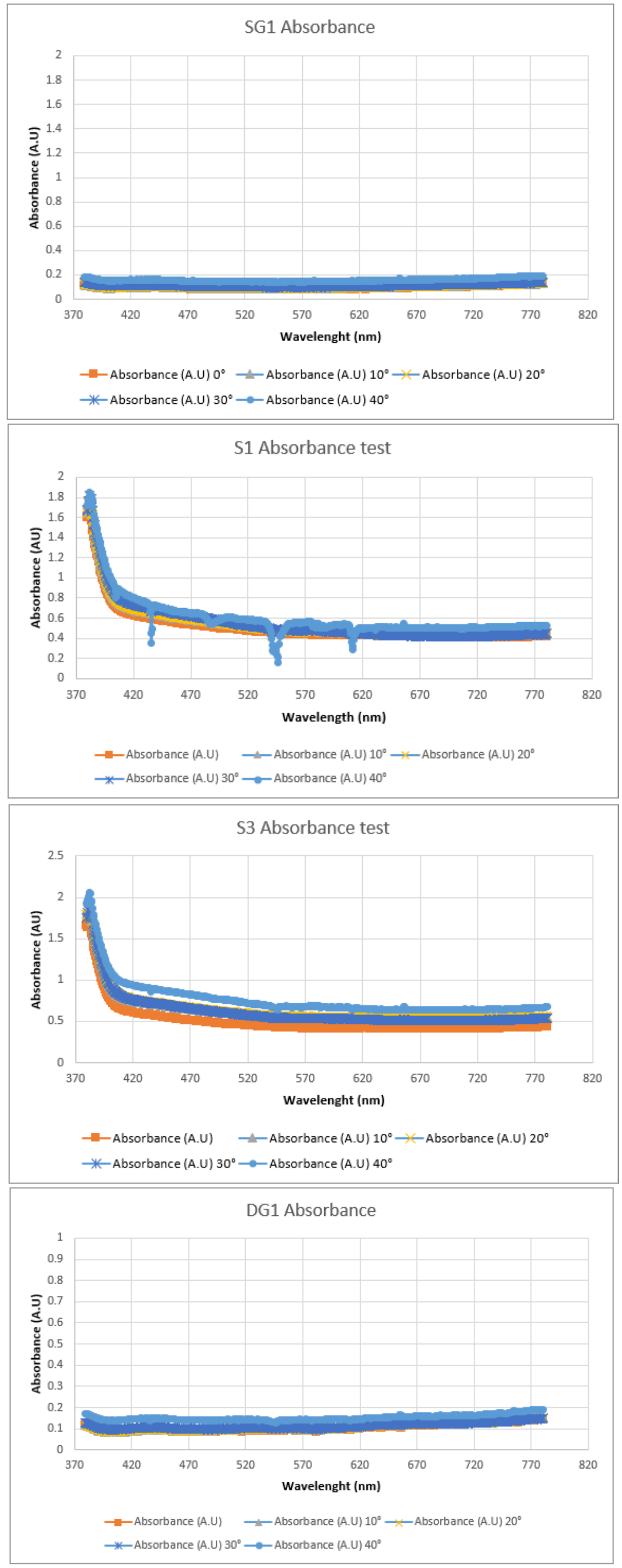

Fig. 7. The absorbance test results for the samples.

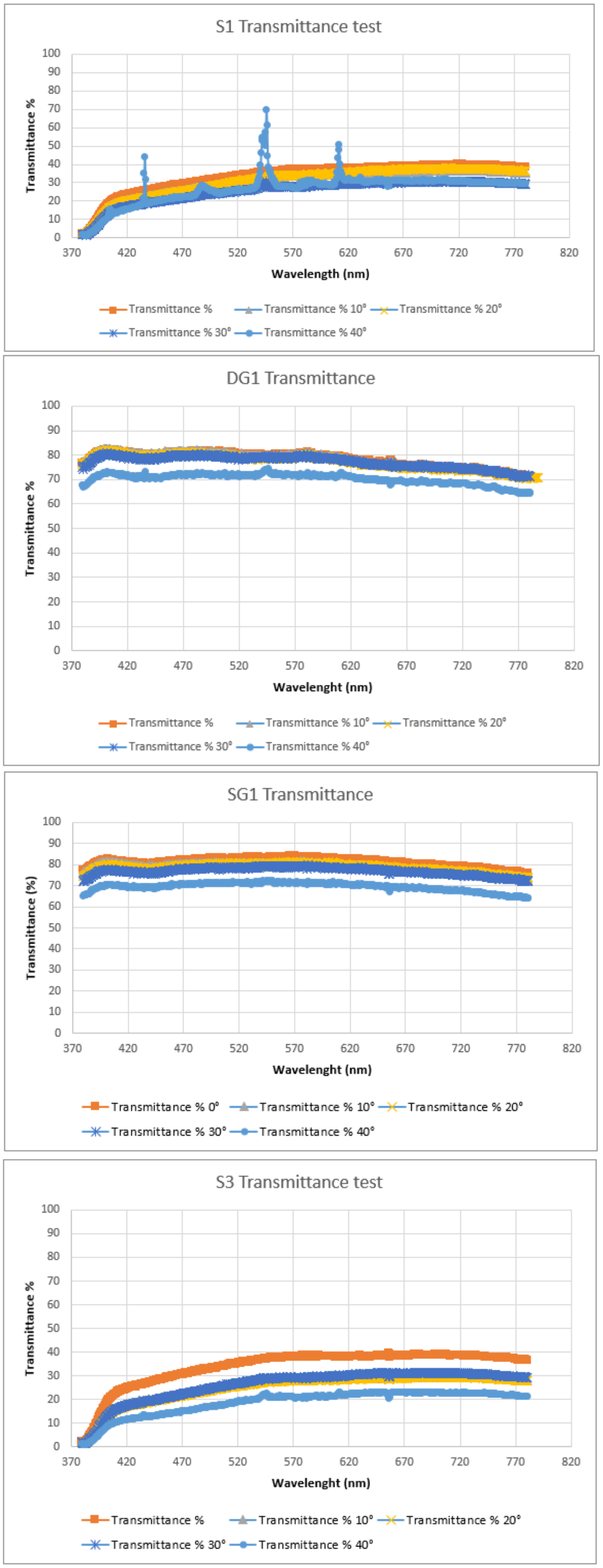

Fig. 8. The transmittance test results for the samples.

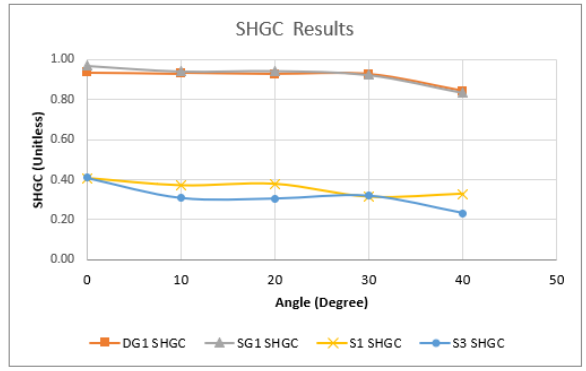

Fig. 9. SHGC Results

TABLE IV
THE AVERAGE U-VALUE

Sample	U-Value (W/m^2.K)
DG1	3.78
SG1	6.21
S1	4.36
S3	2.93

2) *U-Values Results*

As mentioned earlier, the U-Value assesses the amount of energy that passes through the glazing system by taking into account both the transfer of radiation and convective heat between the inner and outer surfaces of the glass. A lower U-value indicates a better insulating capacity for the glazing system.

According to the experimental findings, both tested samples of the CdTe STPV glazing system exhibit better insulation properties compared to conventional single and double-glazing samples, regardless of their structure. This leads to reduced heating load when incorporated into buildings, as evident by Fig. 10 and the sample's average U-Values as shown in Table IV.

It needs to be noted that the existence of solar cells adds a new dimension to the glazing systems. The S1 and S3 samples have an electrical profile that needs to be identified. The open circuit voltage for S1 is 10.17 volts, whereas the open circuit voltage for S3 is 9.95 volts. The short circuit current for S1 is 122.10 m. Amps. Whereas the short circuit current for S3 is 95.7 m. Amps.

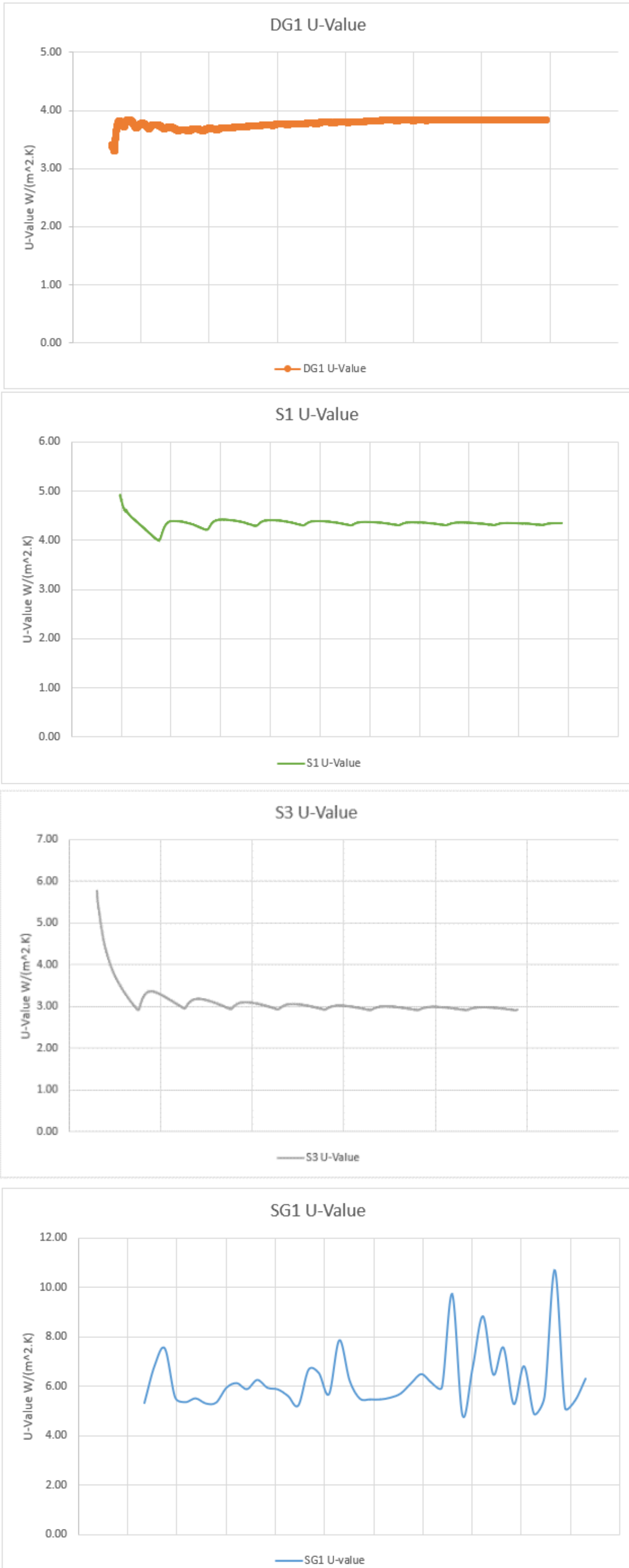

Fig. 10. U-Value Results for all samples

IV. Conclusion

This work thoroughly demonstrated the experimental approach to measure the thermal and optical properties in a controlled setting, using two CdTe STPV glazing samples. The findings from these samples are then compared to single and double-glazing reference samples. The thermal characteristics are classified into two metrics the U-Value and the SHGC. The U-value results for STPV samples are similar to the double-glazing system or better, where the U-Value for the DG sample is 3.8 W/(m^2.K), whereas the U-Value for S1 and S3 are 4.36, 2.93 W/(m^2.K) respectively. As for the SHGC, the results indicate that utilising STPV glazing systems would reduce the cooling demand as it restricts the amount of solar irradiance entering the indoor environment reducing the passive heating element that glazing systems provide.

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References

[1] J. Peng *et al*, "Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window," *Appl. Energy*, vol. 242, pp. 854-872, 2019. . DOI: 10.1016/j.apenergy.2019.03.107.

[2] Y. Cheng *et al*, "Investigation on the daylight and overall energy performance of semi-transparent photovoltaic facades in cold climatic regions of China," *Appl. Energy*, vol. 232, pp. 517-526, 2018. . DOI: 10.1016/j.apenergy.2018.10.006.

[3] N. Skandalos *et al*, "Overall energy assessment and integration optimization process of semitransparent PV glazing technologies," *Prog Photovoltaics Res Appl*, vol. 26, *(7)*, pp. 473-490, 2018. . DOI: 10.1002/pip.3008.

[4] J. Peng *et al*, "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, 2016. . DOI: 10.1016/j.apenergy.2015.12.074.

[5] S. Zhang *et al*, "Scenarios of energy reduction potential of zero energy building promotion in the Asia-Pacific region to year 2050," *Energy (Oxf.)*, vol. 213, pp. 118792, 2020. . DOI: 10.1016/j.energy.2020.118792.

[6] T. Miyazaki, A. Akisawa and T. Kashiwagi, "Energy savings of office buildings by the use of semi-transparent solar cells for windows," *Renewable Energy*, vol. 30, *(3)*, pp. 281-304, 2005. . DOI: 10.1016/j.renene.2004.05.010.

[7] E. M. Saber *et al*, "PV (photovoltaics) performance evaluation and simulation-based energy yield prediction for tropical buildings," *Energy*, vol. 71, pp. 588-595, 2014. . DOI: 10.1016/j.energy.2014.04.115.

[8] S. Xu *et al*, "Optimal PV cell coverage ratio for semi-transparent photovoltaics on office building façades in central China," *Energy & Buildings*, vol. 77, pp. 130-138, 2014. . DOI: 10.1016/j.enbuild.2014.03.052.

[9] Y. Fang *et al*, "Experimental validation of a numerical model for heat transfer in vacuum glazing," *Solar Energy,* vol. 80, *(5),* pp. 564-577, 2006. . DOI: 10.1016/j.solener.2005.04.002.

[10] P. Robinson and J. Littler, "Advanced glazing: Outdoor test room measurements, performance prediction and building thermal simulation," *Build. Environ.,* vol. 28, *(2),* pp. 145-152, 1993. Available: https://www.sciencedirect.com/science/article/pii/0360132393900488. DOI: 10.1016/0360-1323(93)90048-8.

[11] T. T. Chow *et al*, "A Comparative Study of PV Glazing Performance in Warm Climate," *Indoor + Built Environment,* vol. 18, *(1),* pp. 32-40, 2009. . DOI: 10.1177/1420326X08100323.

[12] 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," *Solar Energy,* vol. 22, *(4),* pp. 351-354, 1979. Available: https://www.sciencedirect.com/science/article/pii/0038092X79901889. DOI: 10.1016/0038-092X(79)90188-9.

[13] P. Wouters *et al*, "The use of outdoor test cells for thermal and solar building research within the PASSYS project," *Build. Environ.,* vol. 28, *(2),* pp. 107-113, 1993. Available: https://www.sciencedirect.com/science/article/pii/0360132393900444. DOI: 10.1016/0360-1323(93)90044-4.

[14] T. J. Kim *et al*, "Development and evaluation of a measurement method and system for solar heat gain coefficient and thermal transmittance," *Materials Research Innovations,* vol. 19, *(sup5),* pp. S5-964-964, 2015. Available: https://www.tandfonline.com/doi/abs/10.1179/1432891714Z.0000000001230. DOI: 10.1179/1432891714Z.0000000001230.

[15] American Society of Heating, Refrigerating and Air-Conditioning Engineers and Ashrae, *2013 ASHRAE Handbook: Fundamentals.* 2013Available: https://books.google.co.uk/books?id=b6rYnAEACAAJ.

[16] M. Tamm *et al*, "Development of a Reduced Order Model of Solar Heat Gains Prediction," *Energies (Basel),* vol. 13, *(23),* pp. 6316, 2020. Available: https://search.proquest.com/docview/2467260197. DOI: 10.3390/en13236316.

[17] J. S. Carlos and H. Corvacho, "Evaluation of the performance indices of a ventilated double window through experimental and analytical procedures: SHGC-values," *Energy and Buildings,* vol. 86, pp. 886-897, 2015. Available: https://dx.doi.org/10.1016/j.enbuild.2014.11.002. DOI: 10.1016/j.enbuild.2014.11.002.

[18] The International Organization for Standardization, "BS ISO 9869-1:2014: Thermal insulation. Building elements. 7IIn-situ7R measurement of thermal resistance and thermal transmittance: Heat flow meter method," 2014.

[19] The International Organization for Standardization, "BS ISO 19916-3:2021: Glass in building. Vacuum insulating glass: Test methods for evaluation of performance under temperature differences," 2022.

[20] The International Organization for Standardization, "BS ISO 19916-1:2018: Glass in building. Vacuum insulating glass: Basic specification of products and evaluation methods for thermal and sound insulating performance," 2018.

[21] The International Organization for Standardization, "BS EN ISO 52022-3:2017: Energy performance of buildings. Thermal, solar and daylight properties of building components and elements: Detailed calculation method of the solar and daylight characteristics for solar protection devices combined with glazing," 2017.