MEASUREMENT OF SOLAR HEAT GAIN COEFFICIENT FOR SEMI-TRANSPARENT BUILDING-INTEGRATED PHOTOVOLTAICS IN THE TROPICS

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ABSTRACT: The building envelope in tropical climate conditions continuously receives a high amount of solar radiation throughout the year. Depending on the insulation properties of the building materials used for the roof, wall and fenestration systems, it has a major impact on air-conditioning load and energy utilization in the building. Fenestration systems, in particular, should have a low Solar Heat Gain Coefficient (SHGC) to comply with building codes and regulations such as those of the Singapore's Building & Construction Authority (BCA) in order to achieve the recommended Envelope Thermal Transfer Value (ETTV). This paper investigates the thermal performance of semi-transparent building integrated photovoltaics (BIPV) in a "Japanese bamboo blinds" design using state-of-art indoor laboratory measurements for SHGC in a calibrated Calorimeter Hot Box under steady-state conditions. Results of this study indicate that indoor measurements comply with international standards and provide accurate quantification of the thermal characteristics of semi-transparent BIPV, which has great deployment potential for energy efficient buildings in the tropics. Furthermore, based on ETTV sensitivity analysis, the integration of such glass-glass BIPV into the fenestration system will allow buildings to achieve Gold, Gold Plus, and Platinum Green Mark award with window-to-wall ratios of up to 0.51, 0.40, and 0.36, respectively.
Keywords: Building-Integrated Photovoltaics, BIPV, Solar Heat Gain Coefficient, Thermal Properties.

1 INTRODUCTION

The growing energy demand globally, coupled with increasing environmental concerns call for new applications to utilize sustainable energy generation technologies. This even more so in an urban context where the resources for renewable energies are limited and space is often constraint, like for the case of Singapore, a city-state located close to the equator. In the tropical climate of Singapore, building façades receive a high amount of solar energy throughout the year. In order to harvest the clean energy from the sun and reduce greenhouse gas emissions, one growing trend is to replace conventional materials of the building envelope with building integrated photovoltaics (BIPV). Such advanced building skins (e.g. in the form of solar fenestration systems, curtain walls or shading devices with photovoltaic elements) are also critical for achieving Zero-Energy Buildings (ZEB) or even Positive Energy Buildings (PEB), as they not only enable on-site energy generation but also reduce the solar heat gain into the building. It is pre-requisite though that BIPV elements still provide typical functionalities of the building envelope as divider between the external and internal environment, be it as weather shield, noise protection, heat insulations, as well as aesthetics. More detailed definitions for BIPV as a function of building component or construction product can be found in the two EN standards: EN 50583-1:2016 [1] for BIPV modules and EN 50583-2:2016 [2] for BIPV systems. Both refer to essential building requirements specified in the European Construction Product Regulation CPR 305/2011, such as the mechanical and structural norms, energy economy, sustainable use of natural resources, weather, fire and noise protection, as well as safety aspect on both module and system levels. The application of BIPV technologies is not limited to the roof, and rather expands also to claddings, spandrels, balconies, parapets, shading devices, roof tiles, prefabricated systems, flexible foils, skylight, and fenestration solutions. The latter includes windows, skylights, and curtain walls, as increasingly adopted by architects. Apart from its multi-functionality, sustainable fenestration systems should also consider energy efficiency measures following local building codes, best practices in sustainable designs, and comply with international standards. Nevertheless, up to now, there has been lack of research that quantifies the thermal characteristics of innovative BIPV technologies and compliance with building codes and standards to encourage the building industry to further adopt BIPV solutions.

This paper aims to describe the procedures for the accurate quantification of the thermal properties, in particular the determination of the so-called "Solar Heat Gain Coefficient", SHGC (often also referred to as the "g-value") of semi-transparent building integrated photovoltaic modules under steady-state laboratory conditions using a calibrated Calorimeter Hot Box. The work also addresses the compliance with existing building regulation and Green Mark certification in Singapore. The proposed methodology is meant to assist façade engineers and building professionals to make informed decisions on the adoption of BIPV and its impact on energy performance of the building envelope at an early design stage.

2 EXPERIMENTAL SET-UP

Calorimeter Hot Box Description. The design of the Calorimetric Hot Box at the Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS) was inspired by the requirements of the building industry to test building materials and entire façade elements in real-world dimensions of up to 1.5m x 1.5m. The Calorimeter Hot Box consist of i) a metering box, ii) a guarding box, iii) a surround panel with external air curtain, and iv) a solar simulator. A schematic diagram of the experimental set-up of SERIS' Calorimeter Hot Box is illustrated in Fig. 1.

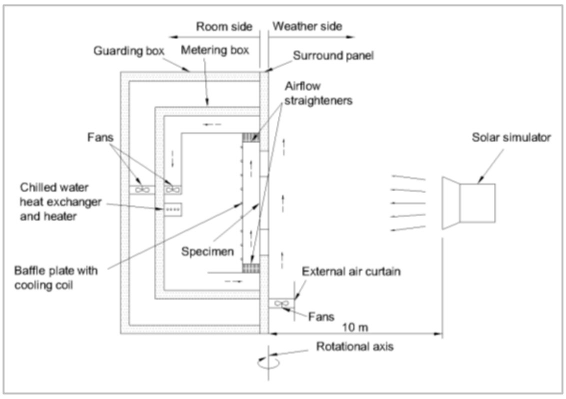

Figure 1: Schematic drawing of the experimental set-up of SERIS' Calorimeter Hot Box for Solar Heat Gain Coefficient (SGHC) measurements.

The diagram also shows details of the "room side" (left) and the "weather side" (right) of the Hot Box. The room side incorporates chilled water heat exchanger, heater, indoor fans, all installed in a metering box and a guarding box. The surround panel is designed for installation of the specimens with various opening dimensions from 30cm by 30cm to 1.5m by 1.5m. The weather side simulates the "weather conditions" with an air curtain (using external fans) and an indoor sun simulator, as shown in Fig 2. The sun simulator (18000ARRIMAX, ARRI 18/12 solution) with a single 18 kW metal halide lamp (HMI 18000W/SE/GX51, Osram) is installed 10m away from the specimen to provide greater uniformity and a small divergence angle. Details of the SERIS in-house procedures for Calorimetric measurements for SHGC are summarized in [3].

Calorimeter Hot Box Calibration. The major components of the Calorimeter Hot Box, for example the high-presicion volumetric flow meters (Emerson) and the pyranometer (CPM11, Kipp&Zonen) are regularly calibrated, following ISO 17025 protocol. Prior to the actual measurement of the fenestration system, the Calorimeter Hot Box is undergoing a number of calibration procedures as outlined in NFRC 201:2010 - *Standard Test Method for Measuring The Solar Heat Gain Coefficient of Fenestration systems Using Calorimetry Methods (NFRC 2001)* [4]. One of the primary calibrations of the calorimeter, which is carried out prior to any facade element tests, is the measurement of a ASHRAE "reference glazing system" (clear single glass) to ensure the accuracy of the apparatus against known values.

Figure 2: Photographs of the metering box with installed specimen (left), and indoor sun simulator (right).

Description of the specimen. The tested specimen is a commercially available, multifunctional glazing element with see-through mono-crystalline silicon solar cells that are cut into stripes and re-arranged in the form of a "Japanese bamboo blinds" design (AGC, "Sudare"), as illustrated in Fig 3.

Figure 3: Original sample of semi-transparent BIPV: view from indoors (left), view from outdoors (right).

This semi-transparent glass-glass PV module consists of the following layers: i) glass; ii) ethylene vinyl acetate (EVA); iii) c-Si solar cells; iv) EVA; v) glass. The module configuration and detailed cell arrangement are shown in Fig. 4. The summary of the technical specifications is given in Table I.

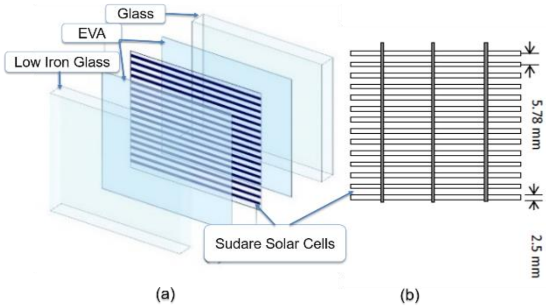

Figure 4: Multifunctional glazing element: (a) glass-glass BIPV layers configuration; (b) detailed design of cell arrangement.

Table I: Semi-transparent glass-glass BIPV module specification.

Module size	1000mm x 1000mm x 128mm
Weight	~30 kg/m^2
Cell type	"Sudare" mono c-Si cell
Cell ratio	30.7%
Number cells per module	56 pcs
Maximum Power, P_{max}	49 W
Fill Factor	84.7

Calculation procedure. Indoor evaluation of the SHGC of the semi-transparent BIPV in a "Japanese bamboo blinds" design as a function of the fenestration system has been carried out at SERIS' Calorimeter Hot Box for hot climates ("summer conditions"). During the test, the indoor side, i.e. the metering box and the guarding box are maintained at steady-state temperature and airflow conditions. On the outdoor side, the specimen is exposed to the external air-curtain and solar radiation from the solar simulator. Steady state heat flow through the specimen due to the transmission of solar radiation heat was measured to derive the SHGC value as follows:

$$SHGC = Q_S/(I \cdot A_s) \quad (1)$$

where Q is the heat flow rate transmitted through the specimen in[W]; A_s is the specimen area in [m^2]; and I is the incident solar irradiance in [W/m^2].

The heat flow rate is calculated by the following formula:

$$Q_S = -(Q_{CW} + Q_E + Q_{Wl} + Q_{Fl} + Q_{SP} + Q_U) \quad (2)$$

Where Q_S is heat flow through the specimen due to solar heat gain during the steady state in [W]; Q_{CW} is the heat flow discharged by chilled water in [W]; Q_E is heat loss from the electrical devices in [W]; Q_{Wl} is the metering box heat loss, determined during wall loss calibration in [W]; Q_{Fl} is the surround panel flanking heat loss, as detected through flanking loss calibration procedures in [W]; Q_{SP} is the heat loss through the surround panel in [W]; Q_U is the heat flow through the specimen due to U-value (thermal transmittance) in [W]. Table II summarizes the measurement results for determination of SHGC of the "Sudare" semi-transparent BIPV module. The final SHGC for the measured specimen was: 0.45 ± 0.01.

Table II: Measurement results for semi-transparent BIPV.

Specimen	"Sudare" BIPV
Average width (original)	1000 mm
Average length (original)	1000 mm
Average thickness	128 mm
Test duration	8 hours
Laboratory ambient temperature	21.6 – 27.2 °C
Laboratory relative humidity	43 – 52 %
Laboratory barometric pressure	1.00 – 1.01 bar
Metering air temperature	24 °C
External air curtain temperature	27.3 °C
Metering airflow velocity	0.2 m/s
External air curtain velocity	2.2 m/s
Heat exchange with chilled water loops, $\boldsymbol{Q_{Chilled\ water}}$	-279 W
Heat exchange with electrical devices, $\boldsymbol{Q_{Electrical\ devices}}$	100.4 W
Metering box wall heat transfer, $\boldsymbol{Q_{Wall}}$	8.7 W
Flanking heat transfer, $\boldsymbol{Q_{Flanking}}$	9.6 W
Surround panel heat transfer, $\boldsymbol{Q_{Surround\ panel}}$	8.1 W
Specimen thermal transmission, $\boldsymbol{Q_U}$	3.7 W
Specimen heat transfer, $\boldsymbol{Q_{Specimen}}$	148 W
Mean solar irradiance, $\boldsymbol{I_{Solar}}$	589 W/m^2
Specimen area exposed to solar radiation, $\boldsymbol{A_{Specimen}}$	0.66 m^2
Solar heat gain coefficient (SHGC or G), $\boldsymbol{G}$	**0.45 ± 0.01**

3 COMPLIANCE WITH BUILDING CODES AND REQUIREMENTS

Prevailing building regulations and codes enable architects, engineers, and building professionals to evaluate the compliance of a proposed building design with local energy codes. In 1975, firstly proposed by ASHRAE, the thermal performance index called "Overall Thermal Transfer Value" (OTTV), was adopted as a regulatory control of air-conditioned buildings by the Building Construction Authority (BCA) of Singapore [5,6]. The original OTTV equation was then modified to the Singapore climate conditions and replaced by the so-called "Envelope Thermal Transfer Value" (ETTV).

Three basic components of heat gain through external building materials, walls and windows, are incorporated into the ETTV equation. These are i) heat conduction through opaque walls; ii) heat conduction through glass windows; and iii) solar radiation through glass windows. These heat components are averaged over the area of the building envelope to accurately characterise the thermal performance of the envelope for air-conditioned non-residential buildings, in form of a single ETTV. The underlying equation is dependent on many factors, including outdoor and indoor environment, SHGC and U-value. The formula is as follows:

$$ETTV = 12(1 - WWR)U_w + 3.4(WWR)U_f + \\ +211(WWR)(CF)(SC) \quad (3)$$

where WWR is the window-to-wall ratio, U_w is the U-value of the opaque wall, U_f is the U-value of the fenestration system with correction factor (CF) for solar heat gain through fenestrations, SC is the fenestration shading coefficient, which is impacted by the SHGC, following this equation:

$$SC = \frac{Solar\ heat\ gain\ coefficient (SHGC)\ of\ any\ glass}{Solar\ heat\ gain\ coefficient\ (SHGC)\ of\ a\ 3mm\ clear\ glass} \quad (4)$$

The physical meaning of the ETTV is the averaged heat flux during air-conditioned active hours, relative to the entire envelope area, expressed in units of [W/m^2]. It is important to highlight that the ETTV is now a minimum mandatory standard, regulated under the BCA Green Mark Scheme (GMS) certification. Furthermore, the latest Green Mark requirements for non-residential buildings (NRB), the 5th edition of the GMS, have been tightened with regards to various threshold levels. The acceptable ETTVs now range from 45 W/m^2 for Gold, 40 W/m^2 for Gold Plus, and 38 W/m^2 for Platinum Green Mark [7].

In determining the compliance of the semi-transparent BIPV modules with prevailing building codes in Singapore and the benefits for obtaining Green Mark certifications, further sensitivity analysis of the ETTV has been carried out.

A reference building was defined for the calculation of ETTV for South, North, West, and East orientations with relevant solar correction factors (CF). A representative 20-storey office building with 30m width and 30m depth and a ceiling height of 3m was selected. The window-to wall ratio (WWR) was varied from 10 percent to 90 percent. For simplicity, lightweight wall construction with thermal insulation was assumed for all walls, with a U-value (U_w) of 1.5 W/(m^{2}K). Five typical architectural fenestration systems were compared for the ETTV calculations: 1) 3mm single-pane clear glass; 2) single-pane tinted glass; 3) double-pane (DGU) clear; 4) double-pane (DGU) low-E; 5) semi-transparent BIPV (Sudare). The thermal properties of the 5 fenestration systems are summarised in Table III.

Following equation (3), the ETTV for each fenestration system was calculated, while varying the window-to-wall ratio (WWR), based on their thermal properties i.e. SHGC and U-Value.

The ETTV values of the typical glazing materials was calculated for each of the cardinal directions to determine compliance with Green Mark Certification Scheme with maximum WWR, see Fig 5.

Table III: Thermal properties of 5 glazing systems.

№	Short name	U-Value	SHGC	SC
1	3mm clear glass	5.33	0.87	1.00
2	Single tinted	5.25	0.42	0.48
3	DGU clear	2.83	0.69	0.80
4	DGU low-E	1.59	0.38	0.44
5	BIPV glass	3.74	0.45	0.52

Note: Unit for U-Value is [W/(m^{2}K)] and for SHGC-Solar Heat Gain Coefficient, SC-shading coefficient is [unit-less].

The results show that integrating semi-transparent BIPV as a function of fenestration systems in buildings has comparable thermal properties to low-E glass, see Fig. 5. This, furthermore, indicates that the BIPV modules are able to comply with existing building requirements regarding the ETTV value to achieve Gold, Gold Plus, and even Platinum Green Mark certification at maximum WWR ratios of up to 0.51, 0.40, and 0.36 on North- and South-facing facades, respectively.

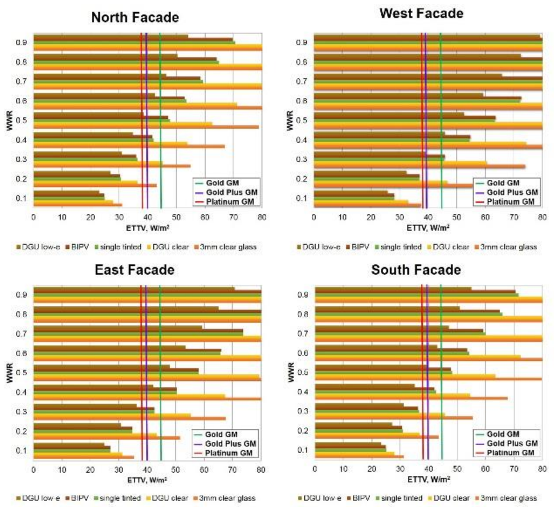

Figure 5: ETTV sensitivity analysis when changing the thermal properties of the glazing (SHGC) and the window-to-wall ratio (from 0.4 as best case to 0.9 fully glazed facade). The Gold and Gold Plus and Platinum Green Mark Award requirement are marked with green, purple and red lines, respectively.

In addition, the GM Scheme also incorporates a numerical scoring methodology, the so-called "Green Mark Score", to assess building design and performance based on degree of compliance with the ideal requirements, as specified in the GM Scheme [7]. According to the total Green Mark Score, including the bonus points under the "Advanced Green Efforts" category, the final Green Mark rating is derived. For example, GM Platinum Rating will be awarded to buildings that score 70 and above points, GM Gold Plus rating for buildings with 60 to 70 points, and GM Gold rating for buildings with 50 to 60 points. Besides, energy efficiency, the deployment of renewable energies is one of the criteria in the building energy performance section. A total of 8 points can be achieved including 0.5 points for a solar energy feasibility study to assess the optimal placement of photovoltaics, 1.5 points for a solar-ready roof (structural, electrical and spatial readiness), and up to 6 points for on-site clean energy generation to offset a building's energy consumption. The Advanced Green Efforts section allows for an additional 5 points for a substantial on-site renewable energy generation. In the bonus section of GM, low heat gain facades, so-called "Tropical Facade Performance" with ETTV equal to 35 W/m^2 an additional point can be scored. This can for example be achieved with semi-transparent BIPV at a WWR of 0.32 on the north facing facade.

4 CONCLUSION

Experimental evaluation of the solar heat gain coefficient (SHGC) of semi-transparent building integrated photovoltaics (BIPV) in a "Japanese bamboo blinds" design as a function of the glazing system has been accurately measured at SERIS' Calorimeter Hot Box for hot climates ("summer conditions"), following international standards and procedures. The results of the study show that the thermal performance of BIPV is comparable with, or better than typical fenestration materials commonly used in the tropics.

This study is meant to primarily assist façade engineers and building professionals to make informed decisions on the adoption of BIPV and its impact on energy performance of the building envelope at an early design stage.

Moreover, the tested specimen complies with BCA Green Mark requirements for ETTV. Based on an ETTV sensitivity analysis, the integration of semi-transparent BIPV into the fenestration system will allow buildings to achieve Gold, Gold Plus and Platinum Green Mark standards with window-to-wall ratios of up to 0.51, 0.40, and 0.36 for South- and North-facing facades, respectively.

Furthermore, the renewable energy generation from the semi-transparent BIPV module becomes even more beneficial for the Green Mark certification, as it allows for additional points, following the GM scoring methodology. BIPV technologies are a critical factor for to achieving the BCA's aspiration of positive-energy low-rise, zero-energy medium-rise and low-energy high-rise buildings in Singapore.

5 ACKNOWLEDGEMENT

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