G-VALUE INDOOR CHARACTERIZATION OF SEMI-TRANSPARENT PHOTOVOLTAIC ELEMENTS FOR BUILDING INTEGRATION: NEW EQUIPMENT AND METHODOLOGY

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ABSTRACT: Whereas the modern architecture trends to an extensive use of glazing elements, buildings are increasingly required to minimize the external energy demand, cutting down the energy needed and covering the residual demand using local energy generation solutions. In this context, the integration of optimized Semi-Transparent Photovoltaic (STPV) elements seems to present a promising energy saving potential, leading to significant reductions of the heating, cooling and lighting loads while the on-site electricity generation is supplied. In mild climate areas, building glazings are required to perform as solar control systems with a low solar factor in order to avoid overheating. However, g-value is frequently unavailable in the data sheet of the STPV elements, making it difficult to design the optimal building solution. In the present work, an indoor testing facility to analyze the solar factor of STPV elements has been further developed and validated. The operating principles of the calorimetric system as well as the experimental data obtained in the validation stage are presented. Results show that the system accuracy and sensitivity are fully adequate to perform detailed analyses of the solar factor of STPV glazings. Furthermore, g-value variations with the transparency degree have been analyzed over different electrical operating points.
Keywords: Building Integrated PV (BIPV), Façade, Experimental Methods, Thermal Performance

1 INTRODUCTION

The current energy policies for buildings focused to improve the energy efficiency of the construction sector [1–3] are likely to increase the market opportunities of BIPV (Building Integrated Photovoltaic) systems in the coming years. However, the standardization of the BIPV elements is still in the development phase due to relative novelty of the sector and the peculiarity of the solutions [4,5] that are required to meet both the building and photovoltaic industries specifications in terms of safety, performance and durability requirements [6,7].

Different studies emphasize how building surfaces could be used to locally generate electricity by integrating BIPV devices into the building enclosure, focusing in particular to the huge potential of these elements when integrated in the façade enclosure of commercial buildings, offices, or institutional buildings, in which the traditional finishing and glazing materials could be easily replaced with the new products [8,9]. In this context, the use of semi-transparent photovoltaic (STPV) elements seems to be particularly interesting, due to the direct impact that the transparent zone of the building envelope has over the heating, cooling and lighting loads [10–12]. To optimize the STPV system in order to minimize the building overall energy demand means to achieve a balance between opposed requirements (such as thermal insulation, solar shading, daylighting, power generation), thus a detailed knowledge of the system behavior is required. Furthermore, the solar gains through the transparent components of the building envelope are one of the major contributors to the cooling loads of buildings [13], that in office building are dominant even in climates commonly considered heating-dominated [14]. To quantify the solar shading capabilities of a transparent component, the solar factor (usually called g-value or Solar Heat Gain Coefficient SHGC) is widely used [13–17]. This percentage parameter measures the permeability of the building component to the solar short-wave radiation (heat transported by long-wave radiation is mostly related to the U-value), including both the solar heat directly transmitted through the material and the heat absorbed and then re-emitted into the enclosed space.

To analyze the thermal performance of buildings components calorimetric testing facility are usually employed [18–23]. Such systems, based on the assessment of the heat flow through the sample in a controlled measuring chamber, are in general complex, expensive, bulky and permanent. In addition, few studies have addressed the potential influence of the different electrical operating conditions that a STPV element may experience (open circuit, short circuit or maximum power production) on its g-value [24,25].

In this work, the operating principles and indoor validation trials of compact calorimetric testing facility [26,27] designed to measure the thermal performance of glazing elements is presented. The transportable device was originally developed at the Laboratory of Energy, Environment and Architecture (LEEA) of the *Haute École du Paysage, d'Ingénierie et d'Architecture de Genève* (HEPIA). It was designed to be temporarily mounted on existing façades in order to evaluate the sun shading property of glazing solutions in real operating conditions, including the dynamic effect of shading devices. In the previous stage of the research the experimental system was extensively used to measure in situ the g-value of glazing systems installed in real buildings at SUPSI (*Scuola universitaria professionale della Svizzera italiana*) [26,27] and HEPIA. The experimental campaign showed on one hand the reliability of the testing facility and on the other a tendency to overestimate the g-value, probably due to a thermal bridge at the interface between the measuring chamber and the glazing under test. For the purpose of this work the device was further optimized and, in order to reduce the uncertainty of the in-situ condition, it was decided to make the measurement in a controlled environment. A continuous light solar simulator, installed in the Swiss PV Module test centre (SUPSI) was used to provide a controllable indoor test condition.

With the main goals of assessing the accuracy of the system, as well as analyzing the g-value sensitivity to the electrical operating point, two laminated glasses, an a-Si double glazing STPV element and three prototypes of mc-Si STPV modules have been used in the controlled conditions testing. Finally linear predictive models have been elaborated in order to predict the actual g-value of a STPV element simply by knowing its geometrical characteristics and operating point.

Section 2 describes the methodology and the experimental testing facility. In section 3 and 4 results are presented and discussed respectively. Finally, in section 4, the main findings of the study are pointed out and conclusions drawn.

2 METHODOLOGY

2.1 Testing facility

Within the framework of a SFOE (Swiss Federal Office of Energy) project, a calorimetric system designed to assess the thermal performances of transparent building elements has been developed. It is composed of two independent measurement boxes to allow the simultaneous test of two glazings, enabling thus the possibility of performing comparative analyses between an element under test and a reference glazing.

The main components of the developed testing facility are (see Figure 1):

- Calorimeter boxes
- Chiller with integrated pump
- Chilled water buffer tank
- Primary water circuit (from the chiller to the buffer tank)
- Secondary water circuits (from the buffer tank to the calorimeter boxes)
- Measurement and control system

Each calorimeter box measures 500x500x500 mm (net internal sizes) and is made of 100 mm thick extruded polystyrene (XPS) board finished with protective plastic layers on the outside and with high absorbing coating on the inside. In the interior of each box, an air to water heat exchanger, an air mixing system consisting of two fans and three temperature sensors (calibrated T-type thermocouples, Class 1, ±0.5°C accuracy) are installed. Two thermocouples are inserted into the thermowells and mounted in the inlet and outlet sections of the heat exchanger in order to measure the water temperature. The interior air temperature is measured by the third thermocouple, placed between the heat exchanger and the box frontal opening, and protected with a shading disk from the direct solar radiation. The incident irradiance on the frontal surface of the glazing element under test is measured with a thermopile pyranometer (secondary standard pyranometer, model Kipp & Zonen CM 11) in compliance with the most stringent ISO 9060 classification [28]. The chiller pump supplies the spiral heat exchanger installed inside the 100 liters buffer tank. This component is necessary to mitigate the water temperature fluctuations at the outlet of the chiller and represents the central part of the hydraulic systems, since it is connected with the chiller by the primary and with the calorimetric boxes by the secondary circuits. Both are physically separated from each other so chilled water is not mixed with the water in the buffer. From here, the secondary water is pumped by the circulator through the heat exchangers installed within the insulated calorimeter boxes. Depending on the cooling requirements, the regulation system (a PID Proportional-Integral-Derivative control system implemented in the datalogger Campbell CR1000) controls the three-way valve which mixes the water from the calorimeter with the chilled water to ensure the appropriate water temperature at the valve outlet, i.e. at the inlet of the radiator. The set point temperature inside the insulated box is set every 30 seconds to the room temperature, in order to minimize the heat flow between the inside of the box and the ambient. To prevent too rapid variations of the control variable that may cause malfunctions of the algorithm, a moving average over 30 minutes of the room temperature is used as set point temperature. High precision turbine wheel flow meter (model Kobold PEL-L045-GN1-F, ±2% accuracy) completes the secondary circuit.

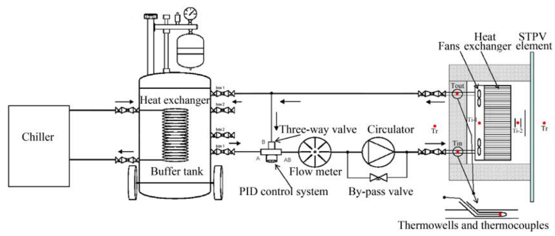

Figure 1. Schematic view of the calorimetric testing facility

The heat is transmitted through the glazings, absorbed inside the insulated boxes and extracted by the internal heat exchangers where cold water from a chilled buffer tank is circulated. The thermal power drawn by the cooling water represents, after some corrections (necessary to take into account the heat losses through the walls and the glass, the thermal effect of the fans and the heat stored in the thermal mass of the system), the solar gains entered into the box across the glazing under test.
The simplified thermal model of the measurement box and equations used to calculate the g-value are deeply explained in [29].

2.2 Calibration stage

The stage of the calibration methodology focused to estimate the specific losses of the box consists in placing the boxes one in front of the other, and introducing within the internal volume a known thermal power by operating the fans, whereas the heat exchanger circulators are kept turned off (Figure 2). In this way the internal air temperature gradually increases, until an equilibrium value is reached. When the steady state has been achieved, it is possible to determine the specific losses by dividing the average internal gains (i.e. the power absorbed by the fans) by the average temperature difference between the inside and the outside of the box. Regarding the specific losses through the glass, a calibration stage is not required since they are calculated by multiplying the glass thermal transmittance by the surface of the g-box measuring opening. The glass thermal transmittance in the case of laminated glazings (laminated glasses and STPV elements F, G and E, as described in Table I) has been calculated according to the

European Standard EN 673:2011 [30], thus it includes both convective and radiative film coefficients. As regards a-Si double glazing STPV element (element BIPVTP/1, Table I), the thermal transmittance value measured by the Swiss Federal Laboratories for Materials Science and Technology [31,32] has been used.

Figure 2. Calibration setup

2.3 Uncertainty analysis

The uncertainty estimation has been carried out according to the Guide to the expression of uncertainty in measurement [33]. The g-value estimation has been carried out with running averages of 40 minutes, to limit the statistical error to negligible values [26]. To quantify the impact of systematic errors on g-value, a glazing element with a known solar factor (g-value=0.38) has been tested [26]. The global uncertainty, calculated as the root of the sum of squares of each individual uncertainty, is ±0.03 [29].

2.4 Experimental measurement

To validate the methodology and the experimental testing facility several tests have been performed using six glazing elements and a steady state CCB class solar simulator [34,35] with the aim of keeping controlled the operational conditions of the STPV modules, namely incident irradiance an solar cells temperature (Figure 3).

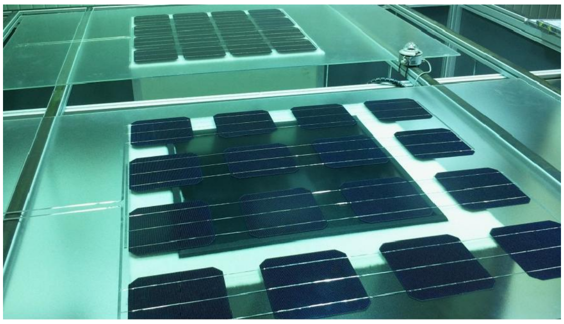

Figure 3. Experimental measurement setup

Regarding the glazings, two identical laminated glasses, a double glazing STPV element of amorphous silicon (a-Si) and three laminated STPV elements of monocrystalline silicon (mc-Si) have been used (Table I) in order to prove the testing facility capability of properly assessing the g-value of different STPV elements, covering a wide range of the Geometrical Transparency Degree (GTD). This geometrical parameter is simply defined as the ratio of the transparent surface of the element in the zone coinciding with the g-box measuring opening to the total surface of the g-box opening. In this sense, it may be worth emphasizing that in all STPV elements the solar cells are fully opaque being the semi-transparency provided by the gaps between them. So the sun-shading properties are more related to the cell-free zones than to the PV cells characteristics.

Table I: Technical specifications of the grazing elements used

Element	Nº	Position	PV Tech.	GTD
Lam. Glass	2	Centered	-	1.00
BIPVTP/1	1	Centered	a-Si	0.10
F	1	Centered	mc-Si	0.22
G	1	Centered	mc-Si	0.60
G	1	No-Centered	mc-Si	0.46
E	1	Centered	mc-Si	0.60

Regarding the measurements performed, each test has been formulated with a specific purpose, as specified in Table II. The first two tests (A and B) focused on assessing the capability of the testing facility in terms of design quality, consistency and accuracy of the g-values measured. Next the testing focused on the impact assessment of the GTD-Electrical Operating Point combination on the g-value. In this sense, test 1 has been performed to analyze the influence of the geometrical degree of transparency on the g-value when the elements are kept in open circuit. In test 2 STPV elements have been connected to independent Main Power Point Trackers (MPPT) in order to analyze how the g-value can vary when it is measured in real operation conditions, i.e. whit the modules operating in the MPP. Finally in test 3 the effect of the short circuit current on the g-value has been addressed.

3 RESULTS

3.1 Preliminary test A – Verifying the consistency of the test boxes

The main aim of this probing is to verify that both the calorimetric boxes measure the same g-value when identical elements are tested. Accordingly, the measurements, carried out using two identical laminated glasses, have been performed and repeated three times in order to compare the results obtained under different irradiance values. Looking at the results showed in Table II, a good consistency of the values can be observed, since in each case the confidence intervals overlap. Furthermore the maximum difference registered between the g-values is of the order of 0.02 that could be considered compatible with the purpose of the testing facility developed.

Table II: G-values measured in the test A

Test	Irradiance	g-value Box1	g-value Box2	Difference
	[W/m^2]			
A1	700	0.96±0.05	0.95±0.06	0.01
A2	600	0.95±0.04	0.95±0.06	0.00
A3	500	0.95±0.05	0.97±0.07	0.02

3.2 Preliminary test B- Verifying the accuracy of the testing facility

To verify the accuracy of the testing facility, the analysis of a known g-value STPV element (BIPVTP/1, see Table I) has been performed in order to compare the solar factor achieved with the g-box with the validated value measured by the *Swiss Federal Laboratories for Materials Science and Technology* [31,32]. Also in this case a very good agreement has been observed between the values, since the result obtained using the g-box was 0.13±0.06 while the reference value was 0.120 ± 0.027. It can be noted that, even if the uncertainty of the measurement performed with the g-box is higher than those of the certified value, also in this case the confidence intervals overlap, so the g-box accuracy can be considered appropriate to perform the indoor analysis of the sun shading properties of the STPV elements.

3.3 Test 1 - Analyzing the GTD effect on the g-value with the elements in OC

In this test the variation of the g-value with the GTD when the modules are in OC has been evaluated. To this end, four measurements were performed: the element F (GTD=0.22) was tested twice in the same identical position in order to ensure the results reproducibility, whereas the element G was tested the first time in the no centered position (GTD=0.46) and the second time in the centered one (GTD=0.60). The results, reported in the Table III, show a good reproducibility of the results since identical g-values have been measured in the two tests conducted with the same element. Also a linear correlation between the GTD and the g-value can be observed: moving from 0.22 to 0.60 in terms of GTD (by a factor 2.7), the g-value increases from 0.57 to 0.77 (by a factor of 1.35).

Table III: Results of the tests 1, 2 and 3, carried out with the elements operating in OC, MPP and SC conditions respectively.

Test	GTD	g-value OC	g-value MPP	g-value SC	Δ%[1]
1.1	0.22	0.57±0.04	-	-	-
1.2	0.22	0.57±0.04	-	-	-
1.1	0.46	0.70±0.06	-	-	-
1.2	0.60	0.77±0.06	-	-	-
2.1	0.22	-	0.54±0.04	-	-5.3
2.2	0.22	-	0.54±0.04	-	-5.3
2.1	0.46	-	0.67±0.06	-	-4.3
2.2	0.60	-	0.75±0.06	-	-2.6
3.1	0.22	-	-	0.60±0.04	+5.3
3.2	0.22	-	-	0.59±0.04	+3.5
3.1	0.46	-	-	0.74±0.07	+5.7
3.2	0.60	-	-	0.81±0.07	+5.2

[1]The relative variations are calculated assuming the g-values measured in open circuit (test 1) as the reference case.

3.4 Test 2 - Analyzing the GTD effect on the g-value with the elements in the MPP

In this experimentation stage the g-value variation of the STPV elements when the modules are operating in the maximum power point (MPP) has been evaluated. To this end, the g-values measured with the elements working at the highest efficiency have been compared with the values registered in open circuit conditions. Results (Table III) show that when the measurements are carried out with the modules operating in the MPP the g-values reduce 5%, 4% and 3% for the elements F, G no centered and G centered respectively in comparison with the results achieved without electrical load. It can be noted that the reduction of the g-value is higher in high power density elements (lower GTD), because a larger amount of the incoming solar radiation is converted into electrical power so the residual fraction converted into heat decreases. The behavior observed has interesting practical implications since it suggests that the g-values provided by the manufacturer of STPV elements, usually measured with no electrical loads connected to the modules (open circuit mode), are not fully representative of the thermal performance of a STPV system operating in the real world, i.e. working at MPP. In this sense, even if the maximum difference registered in the present experimentation is only about 5% in the element F case, it is worth noting that the g-value reduction due to the MPP operation is greater when more efficient solar cells are involved, so probably in the future this effect will be of higher magnitude. Taking into account the relevance of knowing the actual g-value of STPV elements in order to design energetically efficient BIPV solutions such as optimized STPV façades or skylights, it seems that the current g-value characterization methodologies, based for instance on the international standards for glass in building [36–37], are not completely suitable and more realistic testing should be adopted by the STPV elements manufacturers.

3.5 Test 3 - Analyzing the GTD effect on the g-value with the elements in SC

In test 3 the g-value of the elements operating in short-circuit has been analyzed. In this case, the g-values rise for all the elements, with an increase in the range between 3 and 6% in comparison with the measurements performed in the test 1 (OC, see Table III). In this case g-values are the highest registered in the experimental campaign. This may be due to the combination of two effects: on the one hand no electrical power is generated so no power is subtracted from the energy balance and on the other the short-circuit current circulating through the series resistance of the element causes that the operating temperature is greater than in the other cases.

4 DISCUSSION

Regarding the accuracy and reliability of the testing facility, the tests performed to date show that the system can be effectively used to carry out indoor analyses of the g-value of different glazing solutions. The good consistency of the results obtained with the independent measuring boxes (with a maximum relative difference in the order of 2%), as well as the results achieved by comparing the g-value of a STPV element previously tested by an independent laboratory seem to show that the system offers the quality requirements necessary to carry out detailed experimental analysis. In fact, even if a larger number of experimental data covering a wider range of measuring options (including repeated tests and comparisons carried out not only with STPV elements but also with other glazings solutions such as solar control and low emission systems) should be performed in order to deeply assess the accuracy and reliability of the system, results obtained in the preliminary validation stage look promising and lays the foundation for more extensive experimental campaign.

Once the consistency of the test boxes and the accuracy of the testing facility were successfully verified (tests A and B), the variation of the g-value with the transparency (GTD) and the electrical operating conditions (OC, SC and MPP) has been evaluated. Results, summarized in Figure 4, show a linear correlation between the GTD and the g-value. Furthermore, it can be observed that the linear correlation depends on the electrical operating point of the PV element. In this sense, the maximum g-value relative variation produced by the operating point in comparison with the reference case (OC condition) is comprised between -5.3% (MPP case) and +5.3% (SC case) when the element with a GTD=0.22 is considered. Looking at the element with a GTD=0.60, the maximum g-value relative variation due to the electrical operating point is comprised between -3% (MPP case) and +5% (SC case).

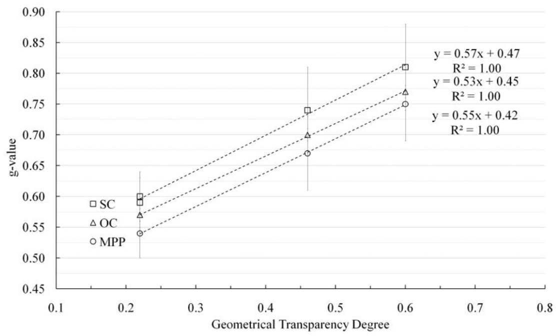

Figure 4: Correlation between the g-value, the GTD and the electrical operating point in the measurement setups analyzed

4 CONCLUSIONS

In this study, equipments and methodologies focused to assess the g-value of STPV elements in indoor conditions has been proposed. The main findings of this work are listed below:

- The indoor testing facility (g-box) developed and the methodology proposed allows the g-value characterization of semi-transparent photovoltaic elements (STPV) with low uncertainty. The measurement system, consisting of a calorimeter system coupled to a steady state solar simulator, has been developed and operated in different measurement setups showing an adequate sensitivity to perform detailed analyses of the g-value variations.
- Validation of the methodology and associated experimental set-up has been done by means of an experimental campaign carried out with several glazing elements, including three prototypes of mc-Si STPV elements characterized by different cells-to-glass ratios. Results show that the g-box is able to properly take into account not only large g-value variations due to different geometrical characteristics, but also smaller changes produced by the electrical operating point of the elements.
- The results obtained in the validation stage of the methodology have been used to extrapolate a correlation between the g-value, the degree of transparency and the operating point of the module. Four linear simple models have been defined, showing that the g-value of the same element could vary up to 11% moving from the short circuit to the maximum power point condition.
- This result suggests that the g-value defined in the technical specification of the STPV element should be measured with the module operating in the maximum power point in order to provide the building designer with a reliable value of the actual sun shading properties of the element.

To conclude, results show that both the electrical operating point and the amount of incident radiation actually modify the solar control properties of the element. Accordingly, it seems that reducing the solar factor to a single value does not allow an adequate estimation of the glazing element behavior in real operation conditions. Furthermore, in the light of the results of the analysis carried out in terms of accuracy and reliability of the improved testing facility, it could be interesting to on the one hand to extend the experimental campaign in controlled conditions to thin film STPV elements and, on the other, use it again to perform a new experimental study in real operation conditions, in order to assess if the tendency to overestimate the g-value observed in the previous experimentation has been reduced.

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