# Design, development and construction of an outdoor testing facility for semi-transparent photovoltaic modules

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*ABSTRACT: Building-integrated Photovoltaics (BIPV) is one of the most promising technologies enabling buildings to generate on-site part of their electricity needs while performing architectural functionalities. A clear example of BIPV products consists of semi-transparent photovoltaic modules (STPV), designed to replace the conventional glazing solutions in building façades. Accordingly, the active building envelope is required to perform multiple requirements such as provide solar shading to avoid overheating, supply solar gains and thermal insulation to reduce heat loads and improve daylight utilization. To date, various studies into STPV systems have focused on their energy performance based on existing simulation programs, or on the modelling, normally validated by limited experimental data, of the STPV modules thermal behaviour. Taking into account that very limited experimental research has been conducted on the energy performance of STPV elements and that the characterization in real operation conditions is necessary to promote an energetically efficient integration of this technology in the building envelope, an outdoor testing facility has been designed, developed and built at the Solar Energy Institute of the Technical University of Madrid. In this work, the methodology used in the definition of the testing facility, its capability and limitations are presented and discussed.*

*Keywords: Building integrated photovoltaic, BIPV modules, Semi-transparent photovoltaics, Energy efficiency, Experimental study*

## INTRODUCTION

Building-integrated Photovoltaics (BIPV) is one of the most promising technologies enabling buildings to generate part of their electricity needs while performing architectural functionalities [1, 2]. A clear example is the use of semi-transparent photovoltaic modules (STPV) integrated in façade, where the active building envelope is required to perform multiple (and sometimes opposed) requirements such as perform as a solar shading in summer to avoid overheating, supply solar gains and thermal insulation in winter to reduce heat loads, provide daylight utilization to reduce lighting loads, allow the outside view to the occupants and supply maximum electrical output. In general, reducing the transparency degree in STPV modules reduces the solar heat gains and daylight availability. However, the electrical output can be improved due to the superior conversion efficiency of low transparency degree modules. Accordingly, a balance should be archived between daylight use, thermal performance and power generation. Glazing elements play an important role in the building envelope to reduce energy demands in terms of heating, cooling and lighting loads.

To date, research on STPV modules has been focused, on the one hand, on estimating the energy performance using different commercial simulation software packages [3-5] and, on the other hand, on modelling the heat transfer process and fluid dynamics behaviour of ventilated façades [6-9].

With regard to experimental research on the energy performance of STPV modules, one of the studies was carried out by Li et al. [10] who tested an a-Si STPV module to determinate the visible and solar transmittances and the daily mean conversion efficiency. The recorded results were used to estimate the performance of the façade system applied to a generic reference office building in terms of energy, environmental and economic issues. The electricity reduction represented about 12% of the annual building demand. Han et al. [11] compared the outdoor performance of a naturally ventilated STPV façade with a conventional clear glass façade. They demonstrated that the conversion efficiency of a-Si PV modules slightly decreases from 4.7% to 4.4% when their temperatures increase about 16°C. Robinson and Athienitis [12] used an experimental setup to validate the simulated workplane illuminance values in an office with a mc-Si STPV module. It was demonstrated that the use of STPV over opaque PV modules can significantly increase the overall net electricity generation of the façade, due to an increased workplane illuminance and thus a reduced lighting load. Chen et al.[13] developed a calorimetric hot box [14] and a solar simulator to measure the Solar Heat Gain Coefficient (SHGC) of five different STPV glazing. They found that with an increasing angle of incidence, the SHGC and power generation are reduced significantly (up to 20%).

In summary, very limited experimental research has been conducted on the energy performance of STPV modules. In this work a experimental testing facility for the integral energy performance characterization (thermal, daylighting and electrical behaviour) of semi-transparent BIPV elements under real operation conditions is presented. It includes the design principles, construction details and validation carried out using four prototypes of a-Si STPV modules. Each module corresponds to a specific degree of transparency moving from 10S (lowest degree, whose visible transmittance value is approximately 0.1) to 40S (highest degree, visible transmittance value of approximately 0.4) with the aim of covering a transparency range representative of the market [2].

## EXPERIMENTAL SETUP

The experimental testing facility, designed, developed and built at the Solar Energy Institute of the Technical University of Madrid, is composed of three independent measurement subsystems for thermal tests, luminous tests and electrical tests. The exterior view of the testing facility is shown in Figure 1.

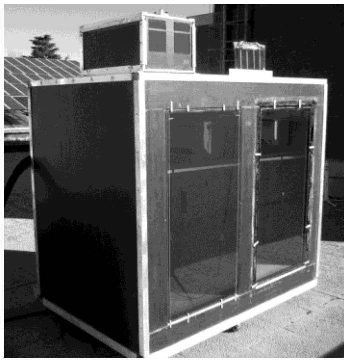

*Figure 1. West and south views of the testing facility. The STPV module is installed on frontal side of the left box. On the frontal face of the right box a code-compliant glass is mounted. On the upper face the scale model used in the daylighting tests and the reference solar cell are installed.*

### *Thermal tests*

Thermal subsystem involves two highly insulated test boxes. The walls are made of 160 mm thick extruded polystyrene (XPS) board with phenolic plywood in both side and protective plastic film as the outer layer. This configuration has a thermal transmittance value of approximately 0.2 W/m$^2$K, which guarantees that the thermal flow through the opaque envelope is at least one order of magnitude lower than the thermal flow through the glazed surfaces, considering that the thermal transmittance of the reference glass and STPV modules are 2.9 W/m$^2$K and 5.7 W/m$^2$K respectively. Vertically, on the frontal face of one of the boxes the STPV module is installed while on the other box a code-compliant conventional glass is mounted. This configuration allows performing a comparative analysis with the following advantages: it minimizes the effect of measurement errors and simplifies the interpretation of results as the reference element is a conventional, well known product. The frontal faces are south oriented. The temperature in both chambers is fixed by two independent air conditioning units. The system can operate in cooling mode or in heating mode: in cooling mode the setup temperature is 25°C while in heating mode is 23°C. Temperatures are monitored by 14 thermocouples (T-type, Class 1, ±0.5°C accuracy) whose locations are shown in Figure 2.

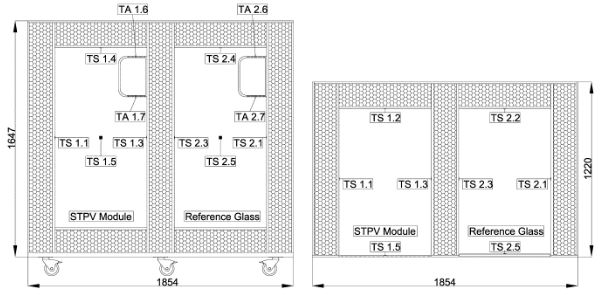

*Figure 2. Dimension of the thermal testing facility and position of the thermocouples. On the left side a vertical section, on the right side a horizontal section. Distances in mm.*

To investigate the thermal behaviour of four different transparency degree STPV modules when they are integrated in a building façade, cooling and heating loads have been calculated in each test-box. The thermal power extracted from each chamber in cooling mode or supplied in heating mode is calculated using the following equation:

$$\dot{Q}[W] = \dot{m}[kg/s] \cdot c_P[J/kg°C] \cdot (T_{out}[°C] - T_{in}[°C]) \quad (1)$$

Where $\dot{m}$ is the mass flow rate of the air crossing the unit, $c_P$ is the specific heat of air at the, moisture and pressure conditions in the box, $T_{out}$ is the air temperature in the outlet vent section and $T_{in}$ is the air temperature in the inlet vent section. The calculation was performed each minute using the constant value of the mass flow rate crossing the unit defined in the technical specifications of the air conditioning units, the specific heat of air calculated for the thermo-hygrometric conditions in the boxes, and the air temperature values measured each minute in the inlet (TA 1.6 and TA 2.6) and outlet vent sections (TA 1.7 and TA 2.7). By integration, daily heating and cooling loads in both test boxes were calculated for 229 days.

Using equation 1 two assumptions have been made:

- The first one is that humidity ratio does not change during the cooling process, thus there is not moisture condensation in the unit coil and only sensible heat is extracted by the unit. There are two reasons to assume this simplification. The first is that the cooling unit was working main time with the same volume air, due to the tightness of the box test, so if there was condensation would occur only in the first stage of measurement. The second reason is that in the summertime the average relative humidity in Madrid is only 40%. In any case this supposition was verified experimentally.

- The second assumption done is that the contribution from the water vapour is relatively small on the total value of the specific heat of moist air and consequently may be neglected. This is because the humidity ratio that corresponds to the air internal conditions (dry-bulb temperature of 25°C a relative humidity of 40% and an altitude of 655 m above sea level approximately) is 0.0085 kg/kg. So, water component on the overall specific heat of moist air is about 1.5% and can be ignored.

To determinate real energy flow gone through STPV module and conventional reference glass, minute values of heat flows through the insulated walls (160mm XPS) were calculated. Flows through the walls were used to correct the loads calculated by equation 1.

### *Daylighting tests*

To perform the daylighting tests a scale model was used whose dimensions duplicate one unit of the reference office originally defined in the European Commission Joule projects REVIS and SWIFT [15]. The 1:10 scale model consists in a light-proof box closed on the frontal side by the STPV element. The element has been shaded partially with a black adhesive foil reproducing the geometry of the façade as shown in Figure 3.

*Figure 3. The 1:10 model used in the daylighting tests.*

To carry out the measurements, three luxmeters Mesa Systemtechnik GMBH MS-Lux (4% max deviation) were installed inside the box and one outside. The position of the measurement points inside the box was established dividing the depth of the reference office into three zones and in the centre of each one was located a luxmeter at the working plane level. The dimensions of the test box and the position of the luxmeters are given in Figure 4. Measurements of the illuminance values inside and outside of the model were carried out both in sunny conditions and in overcast conditions. For this, three typical days were selected and for each of them all the modules were tested measuring indoor and outdoor illuminance values for three times during 15 minutes with a sampling period of 5 seconds.

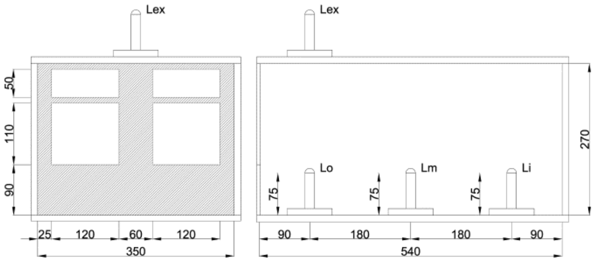

*Figure 4. Dimensions of the scale model and positions of the luxmeters used in the daylighting test. Distances in mm.*

Illuminance values registered under overcast conditions were used to calculate the Daylight Factor (DF) while measures taken under sunny sky conditions, more representative of the local climatology, were used to estimate the daylighting potential provided by modules.

### *Electrical tests*

Electrical tests have been done using a stand-alone configuration. For this purpose a maximum power point tracking (MPPT) battery charger for off-grid PV systems has been used. Monitoring was carried out by measuring every minute the current and the voltage of the PV-module. Irradiance on the vertical plane was measured each minute using a reference solar cell [16]. Taking into account that the angular behaviour of a PV device is mainly defined by the characteristics of the material in contact with the air [17], the similarity between the front glass of the reference solar cell and the STPV modules (low-iron glass, about 3.2mm thick in both cases), ensure that the radiation measured with the reference solar cell represents the effective radiation incident on the STPV modules. Short circuit current was used to calculate irradiance and by integrating it daily irradiation was calculated. Daily conversion efficiency was determined by dividing the daily values of electrical output (normalized to unit area of the module) by the effective irradiation incident on the solar cells. The module efficiency was adjusted taking into account the MPPT efficiency, previously characterized [18].

## RESULT AND DISCUSSION

### *Thermal analysis*

To analyze the thermal performance of the STPV modules, two parameters were calculated from the measurements:

- The first parameter, called *Heat Gain Coefficient* (HGC), is intended to describe the sun-shading performance of STPV modules. Simply, it is the *ratio* between the daily solar gains transmitted inside the test box through the module (per square meter of module) and the daily irradiation available outside on the vertical plane (where the module is installed).
- The second parameter, called *Heat Loss Ratio* (HLR), is used to describe the insulating property of

the module in comparison to a reference code-compliant double glass. This parameter is the ratio between the night-time heat loss from the STPV test box towards the outside and the simultaneous heat loss from the reference glass test box towards the outside. This parameter allows determining the insulating property of the STPV modules in real operation conditions (transient state), complementing the thermal transmittance information determined in laboratory under steady state conditions.

### *Heat gain- Cooling mode from May to October*

The Heat Gain Coefficient (HGC) of the STPV modules and of the glasses was calculated by dividing the daily solar gain by the daily solar irradiation incident on the vertical plane. Taking into account that the solar factor of the reference glass is 0.47, the next step was to select the days in which the HGC of the glass was included in the range 0.47±10%. This range was established to avoid the influence of the extreme days on the measurements and to ensure similar test conditions for all tested STPV modules. When this filter is applied, cooling mode data are reduced to 66 days, distributed from the last days of May to the beginning of October. Using the selected data the average HGC value was calculated for each module. The results are shown in Table 1.

*Table 1. Measurement days, values of the mean HGC, standard deviation (SD) and coefficient of variation (CV) of the HGC.*

| | 10S | 20S | 30S | 40S |
|---|---|---|---|---|
| Days | 18 | 15 | 13 | 20 |
| Mean HGC | 0.655 | 0.660 | 0.679 | 0.734 |
| SD | 0.050 | 0.073 | 0.074 | 0.037 |
| CV | 0.076 | 0.111 | 0.109 | 0.050 |

To determinate if the differences among the mean HGC values are significant, and thus if the degree of transparency affects the sun-shading performance of the STPV modules, an Analysis of Variance (ANOVA) was carried out [19]. The goal of this analysis is to investigate if the between-sample variance is much larger when compared to the within-sample variance, in other words if the variation among groups is largely caused by the different behaviour of the modules, rather than chance variation. The ANOVA analysis showed that the probability that the differences of the mean HGC values shown in Table 1 are due to chance is just 0.0279%. We can therefore reject at 95% confidence (also with $\alpha$=0.01) the null hypothesis that the different transparency grade modules have the same sun-shading performance and accept the alternative hypothesis that they have not. Taking into account that ANOVA does not provide any information about pairwise differences between groups, to investigate differences among the performance of the STPV modules, Scheffe's method was used [19]. It was found that the differences of the main Heat Gain Coefficients are statistically significant between:

- the modules 10S and 40S
- the modules 20S and 40S

To check the reliability of the results and to verify that the results have not been affected by variability of operating conditions during the outdoor test of the STPV modules, ANOVA of mean HGC of the reference glass was carried out. In this case, the result was a p-value larger than significance level $\alpha$=0.05, so we can accept that the testing facility performed constantly during the overall test.

### *Heat loss – Heating mode from November to April*

The Heat Loss Ratio (HLR) was calculated by dividing the night-time heat loss from the STPV test box towards the outside by the simultaneous heat loss from the reference glass test box towards the outside. Afterwards mean HLR and standard deviation values were calculated for each STPV module. The results are summarized in Table 2.

*Table 2. Measurement days, values of the mean HLR, standard deviation (SD) and coefficient of variation (CV) of the HLR.*

| Module | 10S | 20S | 30S | 40S |
|---|---|---|---|---|
| Sample | 42 | 69 | 14 | 38 |
| Mean HLR | 1.421 | 1.439 | 1.391 | 1.422 |
| SD | 0.090 | 0.118 | 0.119 | 0.061 |
| CV | 0.063 | 0.082 | 0.085 | 0.043 |

As expected, the mean HLR is quite constant for all STPV modules and the heat loss through the modules is approximately 40% larger than the heat loss through the reference glass. Comparing the mean HLR, 1.4 approximately, with the ratio between the thermal transmittance of the STPV modules (5.7W/m$^2$K) and the U-value of the reference glass (2.9W/m$^2$K), 2 approximately, it can be concluded that in transient state the insulating performance of the STPV modules is better than expected, based on the steady state thermal transmittance value. ANOVA showed no statistically significant differences in the performance of the STPV modules in terms of insulating capacity.

### *Daylighting analysis*

The daylight study was carried out performing relative and absolute analyses. The relative analysis, expressed by the Daylight Factor (DF), the ratio of the internal illuminance to the external illuminance, available simultaneously, allows predicting the percentage of the light available into the room under overcast sky [20]. Absolute values of illuminance under overcast and sunny skies are useful to estimate the illuminance distribution into the room and to evaluate the daylighting performance of STPV modules.

### *Daylight Factor*

Figure 5 represents the distribution of the mean DF calculated respectively at 0.9m, 2.7m and 4.5m from the module under test. Error bars represent standard deviation values. To calculate the DF, illuminance values were registered under overcast conditions during 15 minutes with a sampling period of 5 seconds. The measurements were performed rotating the modules and were repeated three times for each module in order to ensure similar conditions of illuminance. A total of 2160 values were processed. It can be seen that at 0.9m mean DF ranges between 8.3% (40S) and 3.0% (10S) and at 4.5m DF values range between 2.6% and 1.0% respectively. 20S and 30S modules provide intermediate DF values with 20S very closed to 10S. En each case, DF distribution can be approximated with a power function whose coefficients are shown in the figure. As can be seen in Figure 5 the statistical dispersion decreases from the next to window zone to the internal zone and also decreases as the transparency degree moves from high (40S) to low (10S).

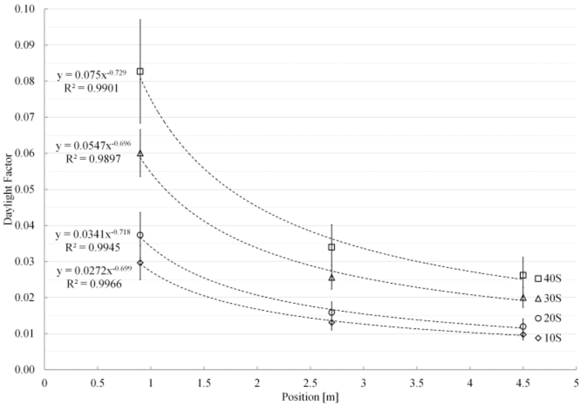

*Figure 5. DF distribution. Error bars represent standard deviation values.*

### *Illuminance*

In different days, illuminance values were registered during 15 minutes with a sampling period of 5 seconds. With the purpose of covering a wide range of lighting conditions, three cases were analyzed:

a. Sunny sky with high exterior illuminance and no direct sunlight over internal luxmeters (typical summer sunny day);
b. Sunny sky with high exterior illuminance and direct sunlight over internal luxmeter Lo (Figure 4) at 0.9m (typical winter sunny day);
c. Overcast sky with low exterior illuminance (typical overcast day).

In Figure 6 the illuminance values registered inside and outside the scale model are shown, corresponding to the first case described above, with high exterior illuminance and no direct sunlight over internal luxmeters. The outdoor illuminance is quite constant and the indoor illuminance is dominated by the degree of transparency of the STPV modules.

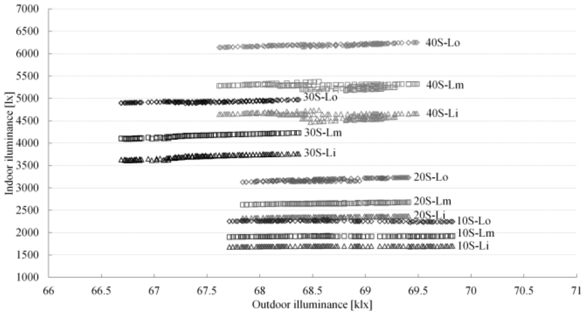

*Figure 6. Illuminance measurements inside (at Li, Lm and Lo positions) and outside the scale model performed during a typical summer sunny day.*

### *Electrical analysis*

To carry out the electrical analysis the modules were monitored under real operation conditions, that is, working at maximum power point. The daily efficiency was calculated by dividing daily electrical energy output per square meter by the irradiation incident on the vertical plane. Results are summarized in Table 3. The efficiency decreases with increasing transparency degree, except for the module 30S which has provided the highest value. In any case, the mean conversion efficiency values range between 2.1% (40S) and 3.2% (30S).

*Table 3. Measurement days, mean, standard deviation (SD) and coefficient of variation (CV) of the daily conversion efficiency (η).*

| Module | 10S | 20S | 30S | 40S |
|---|---|---|---|---|
| Sample | 37 | 105 | 54 | 91 |
| Mean η | 2.932 | 2.879 | 3.203 | 2.095 |
| SD | 0.486 | 0.356 | 0.216 | 0.136 |
| CV | 0.166 | 0.124 | 0.067 | 0.065 |

The homogeneity of the climatic conditions during the test, both in terms of irradiation and temperature of the modules, was proved by ANOVA analysis.

## CONCLUSION

In this study, a methodology has been developed for the integral energy characterization of STPV modules, covering thermal, daylighting and electrical performance. The remarkable findings of this work are listed below:

- Validation of the methodology and associated experimental set-up has been done by means of an experimental campaign of one year carried out with four prototypes of a-Si STPV modules covering a transparency range representative of the current market.

- All tested BIPV elements have substantially larger *Heat Gain Coefficients* (*HGC*) than the reference glass. These data suggest that the solar protection function provided by this configuration of the STPV modules is in general not satisfactory.
- The *Heat Loss Ratio* (*HLR*) is constant for all modules and assumes a value of 1.4. Heat loss through the STPV modules measured (transient state) is approximately 40% larger than heat loss through the reference glass, whereas the thermal transmittance of the STPV modules (U-value) is approximately twice the thermal transmittance of the reference glass. This result demonstrates that a characterization in real operation conditions is necessary to describe and predict the actual performance of STPV modules.
- *Daylight Factor* (*DF*), calculated under overcast sky conditions, presents a potential function distribution. In the close to window zone *DF* ranges between 3% (10S) and 8.3% (40S) whereas in the furthest zone from the window *DF* ranges between 1% (10S) and 2.6% (40S).
- Indoor illuminance values registered on the work plane under sunny conditions in the close to window zone vary between 2257 lx (10S) and 6191 lx (40S). In the most internal zone illuminance values vary between 1692 lx (10S) and 4616 lx (40S).
- Unexpectedly, the highest mean efficiency is provided by 30S module (3.2%). Low transparency degree modules (10S and 20S) provide very similar efficiencies being the reduction of the mean efficiency between 10S and 20S less than 2%. Obviously, the results of this analysis, carried out on four modules only, cannot be extrapolated but the findings of this study suggest that the transparency degree is not the most determining factor for the electrical performance of the module.

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