Comparison assessment of BIPV façade semi-transparent modules: further insights on human comfort conditions

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Abstract

Integrated photovoltaic BIPV components and the usage of renewable energy is already a standard for reducing power consumption, but it would also be important knowing the possible contribution to improve comfort and health of building occupants and assessing an operational balance between the energy consumed and produced. This work describes the testing methodology employed by the authors to further study aspects linked to human comfort when using semi-transparent BIPV elements tested in a real setting and outdoor weather conditions. This research aims to analyse the whole set of issues that influence the global energy consumption in a building that use semi-transparent BIPV as a multifunctional building skin in order to improve quality in test and evaluation procedures of BIPV.

Keywords: Building integrated PV; Energy performance; Thermal comfort; Fanger model, Adaptive model;

1. Introduction and general framework

Solar transmission through window glazing affects not only the air-conditioning load of a building, but also the thermal and visual comfort. Most common in building-integrated PV are the so called “see-through” and “light-through” solar systems. Silicon solar cells and thin film solar cells are used today for semi-transparent glasses for windows. Semi-transparency integrated PV can create a pleasant environment allowing natural light to enter the
building and avoiding overheating in summertime while producing electricity. Heat-exchange between the PV module and the building envelope is another crucial problem not only because the energy yield of a PV system is strongly influenced by the operating temperature of the modules but also because semi-transparent PV modules may have a positive or negative impact on the energy consumption to keep indoor comfort conditions. Even though some of these aspects have already been studied by other authors [1, 2], this study aims to further in-depth quantify indoor comfort conditions that can be obtained by different façade integration of semi-transparent BIPV technologies under real conditions and to suggest a testing methodology enable to compare the global energy balance implications: thermal and lighting consumption related to PV energy production.

2. Test facility and monitoring procedures

The test facility consists of two identical test rooms of about 10 square meters each, which reproduce the indoor conditions of a low energy building, in order to reproduce a more realistic BIPV module integration. Commercial custom made glass-glass insulated BIPV modules to be tested were selected with almost the same heat transmission coefficient (U_value 1.2-1.3 W/m²K) and the same transparency degree in the window frame (Light Transmission, Tl 20%). These BIPV modules were placed in a window frame facing South-East 30º. Test facilities are located in north Italy, near Milan (45°35'49'' N, 8°54'32'' E).

2.1. Thermal comfort assessment

In these test rooms different measurement data acquisition and sensors permit to carry out indoor microclimate test, collecting data every minute to generate the evaluation models of comfort. A set of physical characteristics of the air in which we live and describes the qualitative properties of indoors air is called "microclimate". The microclimatic conditions measurements allow studying our comfort sensation. In fact the human body must always maintain a thermal equilibrium, in contrast with the action of the external environment. Temperature, humidity and ventilation levels can also strongly modify this stability. Human body has several thermal adjustment mechanisms to preserve this thermal equilibrium that may cause disturbances and reduce working capacity. Also, human performance in relation to comfort varies greatly by the type of task to be performed (in this research study the task developed in an office with sedentary activity and clothing level suitable for the time period when the test was performed was considered). Not fulfilling with optimum human comfort levels usually cause also an increase on energy consumption by means of adapting the non-comfort present situation to comfort one (for example, when too much irradiation cause overheating inside a room, mechanical air conditioning systems are normally switch on, even if natural ventilation could be an optimal solution in different climates and seasons).

According Fanger model ANSI-AS-ASHRAE Standard, AAS (Standard 55, 1992) [3], basis of the “International Standard” ISO 7730:1995 [4] and also according the Adaptive Comfort Model, European Adaptive Standard EAS, EN 15251:2007-08 [5], the authors have evaluated the relationship by the two standards and the effect on comfort status by using these BIPV insulated glass-glass elements. The method to determine this evaluation comfort models was described by Polo López et al. in [6] and allows to easily quantifying the daily energy consumption [kWh] for conditioning -heating or cooling the indoor spaces- when comfort levels have not been achieved.

International Standard ISO 7730:1995 classification of comfort categories, according to the level of people dissatisfied, recommends comfort conditions acceptable – normal level of expectation, Class II - for values of PPD, Predicted Percentage of Dissatisfied Index <10%, so for -0.5 <PMV, Predicted Mean Vote Index <+ 0.5 that means (values equivalent at Category II in EN 15251:2007-08). PPD 10 Index defines the acceptability range in 80% acceptability, which means that 80% of people feel comfort and do not require any change. The limit value for acceptable range of thermal conditions (comfort limits) varies according to the reference category, and the level of comfort expectations, this result in a range of comfort for a desired time period. Upper and lower comfort limits are calculated, as result of the standard used, by adding and subtracting a few degrees °C (depending on the type of building and energy supply system used to provide thermal comfort) from the optimum operating temperature that were calculated against a base temperature of 20 °C for wintertime and 26°C for summer time for spaces for occupants with metabolic rates ranging of 1.0 to 1.3 (80% acceptability AAS = Top +/- 3.5°C; Category II EAS = Top +/- 3 °C).
The running operative temperature of the test rooms is computed thanks to the data measured by the sensors in the test room and describes combined effects of convective and radiant heat transfer. Operative temperature can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. For the first period studied and monitored, the test rooms were not mechanically conditioned, as regards buildings using mixed-mode techniques or low-energy buildings in EAS approach. In this way it was possible to quantify the energy consumption for heating or cooling by the number of comfort cooling or heating degree days / hours ACDDe and AHDDe as describes by authors in [7], according with the following equations:

\[ E_{cooling} = m \times C_p \times V \times ACDDe \]  
(1)

\[ E_{heating} = m \times C_p \times V \times AHDDe \]  
(2)

### Nomenclature

- **Ecooling** [kJ]: Energy considers necessary to cool the environment
- **Eheating** [kJ]: Energy considers necessary to heat the room
- **m** [kg/m³]: Air density
- **Cp** [kJ/kg K]: Air heat capacity
- **V** [m³]: Volume to be conditioned
- **ACDDe** [K]: Equivalent cooling degree day
- **AHDDe** [K]: Equivalent heating degree day

#### 2.2. Lighting comfort assessment

A luminous test was also performed to determine the absolute Illuminance values [Lux] inside and outside the rooms, under real conditions (clear sky, partially cloudy and overcast sky). Four NESA Srl luxmeter LUXT-A/B/C devices were installed for measurement monitoring each minute. For each room, three luxmeters were placed at the working plane level with a regular distance from BIPV window pane. The illuminance range of these sensors is: 0.02÷2klux (A); 0.2 ÷20klux (B). One sensor was placed outdoor with illuminance range: 2 ÷200klux (C), <8% compliance with standard photopic curve \( V(\lambda) \). Such a test allows to define the overall illuminance ratio of the rooms (percentage of the indoor illuminance to the outdoorl illuminance) and whether the illuminance comfort levels are achieved for the occupancy period (it be supposed 7.00 a.m. to 7.00 p.m.). For the test, 500 Lux are set as minimum level for comfort in offices according to EN 12464-1 [8] This European standard is about the quality aspects of lighting workstations and their direct environment. EN 12464-1 establishes lighting requirements in accordance with the type of work and the visual task. Comfort level is intend as maintained average illuminance level on a reference task area, to ensure the comfort and visual performance required for tasks to be perform. Otherwise, an increment of electrical artificial lighting energy consumption occurs and it will be estimated for each BIPV element.

#### 2.3. Monitoring procedure

In order to assess and compare future tests using different photovoltaic technologies, seasonal test cycles should be performed. A short term weekly monitoring program was employed to compare different BIPV technologies in the same seasonal weather conditions. Here the authors propose a full week of seven consecutive days test cycles, varying BIPV devices each cycle. For repeatable performance values over time and to categorize seasonal test periods standard days established by the IEC 61853-4 [9] were taken as reference. This IEC standard, still under discussion, defines 6 day types and describes the standard time periods and the meteorological data that can be used to assess the energy rating of a PV module for a given location. Quantitative information on the building performances (test rooms) in terms of thermal and electric energy consumptions and in terms of indoor comfort was evaluated for each group of PV modules. The experiments allow comparing the differences, disadvantages and benefits among all systems studied. The same parameters have been monitored in every test room. Indoor and
outdoor ambient parameters are logged to allow a continuable and thorough measurement. Electrical energy performance was also monitored by a Maximum Power Tracker Point, MPPT dispositive, in order to extract at every moment the maximum electrical power that the BIPV modules can deliver.

Testing facilities’ main features, first set of BIPV modules to be tested and the monitoring system simplified scheme are shown in Fig. 1.

![Fig. 1. a) Test Rooms and semi-transparent BIPV modules to be tested (monocrystallyn silicon technology, mc-Si, amorphous silicon thin film single junction, a-Si and copper indium selenide thin film technology CIS); b) Data acquisition system, schematic layout diagram.]

3. Measurement data acquisition and results

3.1. First Test Cycle Analysis

First results presented here relate to the comparison of two thin film technologies, a CIS PV module (copper indium selenide rated output \( P_{mpp} \): \( P_{m@STC} \): 45.00 Wp) with an a-Si PV module (amorphous silicon single junction technology, rated output \( P_{mpp} \): \( P_{m@STC} \): 31.00 Wp).

The most important characteristics of the two BIPV modules studied are illustrated below in Table 1.

<table>
<thead>
<tr>
<th>Test room 116</th>
<th>Test room 117</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CIS</td>
<td>1 a-Si</td>
</tr>
<tr>
<td>2 CIS</td>
<td>2 a-Si</td>
</tr>
<tr>
<td>3 CIS</td>
<td>3 a-Si</td>
</tr>
<tr>
<td>4 CIS</td>
<td>4 a-Si</td>
</tr>
</tbody>
</table>

Table 1: Main PV electrical parameters of the BIPV modules as declared by the manufacturer, in compliance with IEC 61646 for thin film PV modules.

<table>
<thead>
<tr>
<th>PV Module Electrical Characteristic*</th>
<th>Copper Indium Selenide CIS</th>
<th>Amorphous Si a-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output (( P_{mpp} )-( P_{m@STC} ) [Wp])</td>
<td>45.00</td>
<td>31.00</td>
</tr>
<tr>
<td>Short circuit current - ( I_{sc@STC} ) [A]</td>
<td>0.64</td>
<td>0.49</td>
</tr>
<tr>
<td>Open circuit voltage - ( V_{oc@STC} ) [V]</td>
<td>89.70</td>
<td>93.00</td>
</tr>
<tr>
<td>Fill factor - FF</td>
<td>0.67</td>
<td>0.55</td>
</tr>
<tr>
<td>PV module cell area [m2]</td>
<td>0.42</td>
<td>0.56</td>
</tr>
<tr>
<td>Module Efficiency - ( \eta ) [%]</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Cell Temperature Coefficient [%/K]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient ( \alpha ) (( P_{mpp} ))</td>
<td>-0.36%</td>
<td>-0.20%</td>
</tr>
<tr>
<td>Temperature coefficient ( \beta ) (( I_{sc} ))</td>
<td>-0.29%</td>
<td>-0.31%</td>
</tr>
<tr>
<td>Temperature coefficient ( \gamma ) (( V_{oc} ))</td>
<td>+0.05%</td>
<td>+0.08%</td>
</tr>
<tr>
<td>NOCT (^{[\circ C]})</td>
<td>47±3</td>
<td></td>
</tr>
<tr>
<td>Output tolerance (( \Delta P_{mpp} )) [%]</td>
<td>± 10%</td>
<td>± 10 %</td>
</tr>
</tbody>
</table>

*STC (Standard Test Condition: 1.000 W/m², A.M. 1.5, 25°C)
The external climatic conditions for the entire week at the end of October 2011 are characterized by conditions typical of autumn, overcast and partially cloudy days with not very high radiation and mild temperatures (day type IEC 61853-4, MIMT: Medium irradiance, medium temperature). Outdoor maximum average air temperature for the entire week was 14.90 °C and relative minimum average humidity was 62.69%. The average value of minimum dry-bulb air temperature was 7.98 °C and average value of maximum relative humidity was 93.46%. Average maximum irradiance in-plane of PV modules and façade (90 ° tilt) during the test period was 545.29 W/m².

Figures 2(a, b) show some results of this research project. Indoor comfort needs (heating/cooling) have been evaluated according to Fanger comfort indexes (PMV, "Predicted Mean Vote" and PPD "Predicted Percentage of Dissatisfied") and according to the European Adaptive Standard, EAS, EN 15251:2007-08 methodology for free-running buildings “non-mechanically conditioned buildings”, by using the number of hours during occupancy when the operative room temperatures exceed the defined comfort classes (80% acceptability AAS; Category II EAS). When it comes to thermal comfort, operative temperature (To) stands for what humans experience thermally in a space.

![Fig. 2 Samples of weekly comparison of two different BIPV technologies: a) Thermal comfort analysis according Fanger model “International Standard” ISO 7730:1995; b) Thermal comfort analysis according to the European Adaptive Standard, EN 15251:2007-08. Red and blue lines represent the running operative room temperature while green and orange lines represent the comfort limits temperatures (upper and lower level respectively) for Category II (Normal level of expectation in new buildings and renovations –PPD 10).](image)

In Givoni chart [10, 11] as shown in Figure 3, the areas of environmental well-being, thermo hygrometric comfort zones are represented in a psychometric chart, for summer and winter. Other areas identified by letters show the different design strategies through passive solutions to achieve the desired comfort. In this diagram are considered as input data only the values of outside air temperature and relative humidity. The comfort zone is located between 21 °C and 26 °C dry bulb temperature, with a margin of being admitted between 20 °C and 27 °C. Limit for relative humidity is 75-80% in the upper part and 20% in the lower part.

In this diagram indoor conditions (operative temperature and relative humidity) of the test rooms are shown. Outdoor ambient conditions are also presented. The hygro-thermal comfort analysis for this week showed that test room 116 with CIS PV module perform best that test room 117 with a-Si PV module, as ambient conditions reach comfort zone for winter time longer. Ambient outdoor conditions are printed in green colour. It would be possible to reach comfort just with thermal mass strategies, internal gains and solar passive and active strategies.
Fig. 3 Psychometric chart Milne-GIVONI with comfort zones, evaluation of thermal comfort in autumn time for the test facilities.

Figures 4(a, b) shows the global system energy balance per day by considering total energy consumption and photovoltaic energy production. Needs for space heating/cooling and lighting was calculated for the occupancy period. The results indicate that energy consumption for heating and for lighting is almost similar for the two test rooms, but is slightly higher for heating in Test Room 117 where amorphous silicon BIPV modules were installed even if transparency coefficient is the same for the two PV technologies. Energy output of the BIPV modules is higher for CIS PV module than a-Si PV module, as expected.

Fig. 4 a) and b) Global system energy balance chart considering total energy consumption (heating/cooling and lighting) and PV production.

In Figure 5(a), x-axis represent the energy demand (estimated total thermal and lighting energy consumption) and the y-axis represent energy credits as a result of the application of the BIPV modules tested [kWh/day]. The black line represents the ZEB, Zero Energy Building conditions, where energy supply is equal to energy demand. Each point is related to one day of measurement. As regard this test period, neither the BIPV system in Test Room 116 (CIS PV modules) nor BIPV modules in Test Room 117 (a-Si PV modules) covers the overall energy demand any day. The percentage or each single value as ratio in the energy global balance is shown in Figure 5 (b).
3.2. Second Test Cycle Analysis

The second cycle of test presented here shows the comparison of a CIS PV module (copper indium selenide thin film technology, rated output Pmpp: Pm@STC: 45.00 Wp) with a more common mc-Si PV module (mono-crystalline silicon technology, rated output Pmpp: Pm@STC: 85.00 Wp). Measurements were performed at the end of November 2011. The most important characteristics of the two BIPV modules studied are illustrated below in Table 2.

Table 2: Main PV electrical parameters of the BIPV modules, as declared by the manufacturer, in compliance with IEC 61215 and IEC 61646, for the m-Si PV module and for CIS thin film PV module respectively.

<table>
<thead>
<tr>
<th>PV Module Electrical Characteristic*</th>
<th>Copper Indium Selenide CIS</th>
<th>Mono_Crystalline m-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output (Pmpp)-Pm@STC [Wp]</td>
<td>45.00</td>
<td>85.00</td>
</tr>
<tr>
<td>Short circuit current - Isc@STC [A]</td>
<td>0.64</td>
<td>5.54</td>
</tr>
<tr>
<td>Open circuit voltage - Voc@STC [V]</td>
<td>89.70</td>
<td>19.83</td>
</tr>
<tr>
<td>Fill factor - FF</td>
<td>0.67</td>
<td>0.77</td>
</tr>
<tr>
<td>PV module cell area [m2]</td>
<td>0.42</td>
<td>0.50</td>
</tr>
<tr>
<td>Module Efficiency - n [%]</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>Cell Temperature Coefficient [%/K]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient α (Pmpp)</td>
<td>-0.36%</td>
<td>-41.00%</td>
</tr>
<tr>
<td>Temperature coefficient β(Isc)</td>
<td>-0.29%</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient γ (Voc)</td>
<td>+0.05%</td>
<td></td>
</tr>
<tr>
<td>NOCT [ºC]</td>
<td>47±3</td>
<td>48</td>
</tr>
<tr>
<td>Output tolerance (Δ Pmpp) [%]</td>
<td>± 10%</td>
<td>± 5 %</td>
</tr>
</tbody>
</table>

*STC (Standard Test Condition: 1.000 W/m2. A.M. 1.5. 25ºC)

The external climatic conditions for the entire week are characterized by conditions typical of autumn, overcast and partially cloudy days (day type IEC 61853-4 HILT: High irradiance, low temperature). Outdoor maximum
The average air temperature for the entire week was 10.26 °C and minimum average relative humidity was 67.61%. The average values of minimum dry-bulb air temperature was 1.60 °C and relative humidity maximum average values was 97.80%. Average maximum values of solar radiation in-plane of PV modules and façade (90° tilt) was 713.42 W/m².

Figures 6(a, b) again show graphics for indoor comfort needs evaluated according to Fanger approach “International Standard” ISO 7730:1995 and according to the "Adaptive European Standard" EN 15251:2007-08.

Hygro-thermal comfort analysis for this week showed that the testing room 116 with the photovoltaic module CIS, has succeeded better than the testing room 117 with m-Si PV module, since the indoor environmental conditions reach comfort area for wintertime, while the testing room 117 has never done (see Fig. 7). Ambient outdoor conditions are printed in green colour. It would only be possible to reach comfort due to thermal mass strategies, internal gains and solar passive and active strategies.
Results in Figures 8(a, b) that shows the global system energy balance per day by considering total energy consumption and photovoltaic energy production, indicate that energy consumption for lighting is almost similar for the two test rooms but for heating is slightly higher for Test Room with mono-crystalline Silicon PV module. Energy output of the BIPV modules is higher for m-Si PV module than CIS PV module, as expected.

For this test period, as shown in Figure 9(a), energy demand (estimated total thermal and lighting energy consumption) and energy credits is related each other, the BIPV system in test room 117 (m-Si BIPV modules) covers all the energy demand twice, and for two days there was a surplus. Instead the thin film modules placed in Test Room 116 did not cover the energy demand for the whole test period. The percentage or each single value as ratio in the energy global balance is shown in Figure 9(b). Results indicate that energy consumption for heating is higher in Test Room 117 where m-Si BIPV modules were installed even if the heat transmission coefficient is equivalent for the two insulated glass-glass photovoltaic PV technologies (U value 1.2 W/m²K) while solar factor g is 24% for m-Si and 26% for CIS PV module. Lighting consumption is slightly higher in Test Room 116 than Test Room 117 with m-Si PV modules installed (Light transmission coefficient TL, is almost 20% for all modules).

Fig. 9 a) Energy balance chart for the testing period; b) Contribution of the BIPV technologies tested in total energy balance considering total energy consumption (heating/cooling and lighting) and PV production.
4. Scientific innovation and relevance

The results of this research aim to be a new way to investigate characteristics of BIPV modules scarcely measured until today, such as human comfort -thermal comfort and lighting conditions- in order to ease the planning of new and harmonized standards for BIPV systems and components in future. The environmental comfort assessment methodology evaluate aspects such thermal comfort and visual comfort. This last aspect is a parameter to be reckoned because the photovoltaic devices under examination can significantly alter the perception of light but at the same time and, depending on the external environmental conditions, can favour an adequate solar shading in order to decrease glare and unwanted overheating phenomena, these also bound to the indoor thermal comfort. By comparing face to face different technologies under the same boundary conditions it is possible to establish which performs best for the climatic conditions studied. In the same way, the real energy contribution (energy credit) by the photovoltaic system under operating conditions on the overall energy balance of the building has been calculated, weighing complete BIPV energy performance towards NZEBs.

The overall building energy balance, calculated according to the normalized comfort conditions, took into account energy consumption as well as PV energy production as a new BIPV performance index. It will also be possible to assess the problems found when using these BIPV products and to gather information regarding the product data sheets helping manufacturers and architects to easily use PV modules as building elements.

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References


