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Energy saving potential of semi-transparent photovoltaic elements for building integration

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ABSTRACT

Within the building energy saving strategies, BIPV (building integrated photovoltaic systems) present a promising potential based on the close relationship existing between these multifunctional systems and the overall building energy balance. Building integration of STPV (semi-transparent photovoltaic) elements affects deeply the building energy demand since it influences the heating, cooling and lighting loads as well as the local electricity generation. This work analyses over different window-to-wall ratios the overall energy performance of five STPV elements, each element having a specific degree of transparency, in order to assess the energy saving potential compared to a conventional solar control glass compliant with the local technical standard. The prior optical characterization, focused to measure the spectral properties of the elements, was experimentally undertaken. The obtained data were used to perform simulations based on a reference office building using a package of specific software tools (DesignBuilder, EnergyPlus, PVsyst, and COMFEN) to take proper account of the STPV peculiarities. To evaluate the global energy performance of the STPV elements a new *Energy Balance Index* was formulated. The results show that for intermediate and large façade openings the energy saving potential provided by the STPV solutions ranges between 18% and 59% compared to the reference glass.

1. Introduction

BIPV (building-integrated photovoltaics) is one of the most promising technologies enabling buildings to generate part of their electricity needs while performing one or several architectural functionalities [1–4]. In fact, to minimize the final energy demand of buildings, it is necessary firstly to cut down the energy demand needed to guarantee thermal and lighting comfort and then to cover the residual demand using local efficient energy systems [5–7]. In this sense, due to the important role played by the glazing elements in the building envelope to reduce energy demands in terms of heating, cooling and lighting loads, the relationship between façade design and building energy performance has been widely investigated [8–12]. If, on the one hand, the state-of-art best performing commercial fenestration products and future research opportunities have been extensively studied [3,13–15], on the other hand an innovative and emerging technology consisting of using STPV (semi-transparent photovoltaic), transparency provided by separating individual solar cells within the module or by eliminating parts of the solar cells during their manufacturing process) modules integrated in façades has not been appropriately studied yet [16,17].

The lack of knowledge about STPV solutions in terms of global energy performance is particularly emphasized in view of the fact that the active building envelope is required to perform multiple (and sometimes opposed) requirements such as: solar shading in summer to avoid overheating, solar gains and thermal insulation in winter to reduce heat loads, daylighting provision to reduce lighting loads, outside view allowance to the occupants and maximum electrical output supply. Thus, to improve the building overall energy efficiency, the achievement of a balance between these functionalities is required. Nevertheless to date, research on the multifunctional effect of STPV solutions on the building energy balance

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has been limited. Concerning the total building energy demand, Wong et al. [18] presented power generation, thermal balance and daylight models of roof integrated mc-Si (multicrystalline silicon) STPV and incorporated them into EnergyPlus [19] to carry out overall energy consumption analysis in five climate regions in Japan. It was concluded that with appropriate optimization measures (transparent insulation material and opaque movable insulation depending on the climate region) net energy savings in the range of 3.0–8.7% can be achieved relative to the base case of BIPV roof. Miyazaki et al. [20] expounded the effect of thin-film PV elements transmittance and window-to-wall ratio on the energy consumption of office buildings in terms of heating and cooling loads, daylighting and electricity production. Simulations were carried out using EnergyPlus and the main finding was that the total building electricity consumption could be reduced by 55% using optimum STPV windows. Khai Ng et al. [21] used the same simulation tool to examine six commercially available STPV elements. They defined a new index to evaluate the overall energy performance in Singapore and found that BIPV glazing solutions provide an energy savings rate of between 16.7% and 41.3% compared to common window glazing for large façade openings. He et al. [22] compared experimentally and numerically the performance of a-Si PV double and single glazing windows in east China. They found that the double-glazing solution can reduce to 46% the indoor heat gains, improving the indoor thermal comfort level. Bahaj et al. [23] compared the impact of electrochromic glazing, holographic optical elements, aerogel glazing and thin film PV elements on two highly glazed buildings in arid Middle Eastern climates using TRNSYS [24]. They concluded that glazing integrated thin-film PV solutions are potentially the most promising solution providing an annual cooling load reduction of 31%. The same software was used by Song et al. [25] to calibrate the experimental power output of a commercial STPV thin-film module modified into a double-glazed one. It was found that the computed data was 8.5% lower than measured output. An experimental study was performed by Peng et al. [26] in order to assess the thermal performance of a ventilated PV double skin façade in Honk Kong. They studied the variation of the SHGC (solar heat gain coefficient) and U-value depending on the operation mode of the façade, defining the optimum strategy to improve its thermal behaviour under different weather conditions. Park et al. [27] experimentally analyzed the thermal and electrical performance of a double glazing mc-Si element. Various types of glass (such as clear, green, blue and bronze) were used as back sheet of the PV laminate mounted in the insulated glazing, finding that the rear glass hardly affects the PV module temperature and consequently its electrical performance. Chen et al. [28] used an indoor setup (calorimeter and solar simulator) to determine the SHGC of five STPV glazing elements. The sensitivity analysis concluded that with an increasing angle of incident solar radiation, the SHGC and power generation are reduced significantly (up to 20%) whereas the electrical operation conditions reduce the SHGC by only 3–6%, proportionally to the electrical power output of the element. Lu and Law [29] estimated the overall energy performance corresponding to five orientations of a STPV system installed in Hong Kong by integrating the simulation results of thermal, power and visual behaviours. The main finding of the work was that the system would lead to an annual electrical benefit of about 1300 kWh in the best case orientation (south-east).

While recent years have seen an increasing number of building energy codes and standards focused to improve the energy efficiency of the construction sector [30–32], at present a specific standard that considers PV elements as constructive components does not yet exist or it is just starting to emerge [33]. In the specific case of glazing products, useful tools that enable designers to adopt energy effective project solutions, i.e. the integration of simulation software with reliable and detailed optical data like the IGDB (international glazing database) [34] or the newer CGDB (complex glazing database) [35] are being improved constantly, but STPV elements are still not properly considered.

Consequently, it is worth considering the performance of innovative STPV solutions in comparison with well-established constructive elements. Furthermore, a lack of research exists on the performance of multifunctional STPV façade in the Mediterranean region, characterized by a high annual solar irradiation and a wide range of ambient temperatures [16]. For these reasons, a performance comparison with conventional glazing in Mediterranean conditions is necessary in order to assess realistically the energy saving potential that STPV solutions might provide.

In this work the overall energy performance of five BIPV double glazing elements is evaluated in a specific location, Madrid (latitude 40.45°N, longitude 3.71°W, altitude 664 m) whose main climatic characteristics are typical of the Mediterranean Basin ("dry-summer subtropical" climate classified as Csa according to Köppen climate classification) [36]. Each element corresponds to a specific degree of transparency moving from 0 (opaque element) to 40 (highest degree, visible transmittance value of approximately 0.4) to cover a transparency range representative of the market [3,37]. Prior to performing the comparative analysis, the elements have been experimentally characterized in order to obtain the spectral data necessary to execute a reliable simulation, based on the most advanced window modelling method that uses fully characterized spectral properties [38].

Due to the multifunctional role that STPV elements play in the building envelope, which affects heating, cooling and lighting loads, visual comfort as well as power generation, a set of specific simulation tools has been used to correctly characterize the behaviour of each element. To simplify the understanding of the study, the simulations have been applied to a typical office space.

To assess the energy saving potential of STPV solutions, their performances have been compared, over different WWRs (window-to-wall ratios), with a solar control double glass compliant with the Spanish Technical Building Code [30] in terms of U and g values, so supposedly the most diffused solution in the real world. In addition, in order to establish the importance of the transparency degree on the building energy balance, all STPV elements have been compared with each other.

The article content is as follows. Section 2 describes the experimental equipment used to perform the optical characterization of the STPV elements and the spectral data obtained. Section 3 presents the simulation methodology, the reference office model used to carry out the energy performance analysis and the metrics used to evaluate the performance the glazing elements. In Section 4 the results are discussed. Finally, in Section 5, the main findings are summarized and conclusions are drawn.

2. Optical characterization

The basic optical properties required to evaluate the thermal and daylighting performance of STPV multifunctional elements are their spectral reflectance and transmittance, according to EN410:2011 and EN673:2011 standards on glass in building [39,40]. It is worth mentioning that detailed spectral data are not normally available in the technical specifications of glazing systems, where only global characteristics as U-value, g-value as well as visible transmittance are specified by the manufacturers. In this sense, the IGDB [34] is a valuable source of information to perform accurate energy performance calculations of conventional glazing solutions but unfortunately PV industry products designed for building applications such as STPV elements are not yet included in the database. Consequently, in order to perform accurate energy