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Building integration of semitransparent perovskite-based solar cells: Energy performance and visual comfort assessment

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HIGHLIGHTS

- Innovative transparent perovskite-based BIPVs cells were studied.
- Yearly energy yield and visual comfort benefits were calculated.
- The effect of different climate conditions was also investigated.
- Energy yield varied between 10 and 30 kWh/m^2 per year.
- PV cells behaved like solar control films.

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ABSTRACT

This study presents a prediction of the yearly energy production and visual comfort benefits deriving from the adoption of building integrated semitransparent photovoltaic windows. Measured electrical and optical properties of neutral-colored solid-state planar heterojunction perovskite cells, characterized by promising transparency and photovoltaic conversion efficiency, were applied to a hypothetic photovoltaic glazing. Such experimental data were used as input to estimate annual energy production and visual comfort effects. The effect of different climate conditions was also investigated. A south-oriented test-room was modelled, assuming two window-to-wall ratios (WWRs) for office buildings, 19% and 32%, respectively. Energy yield was calculated at different locations showing figures between 20 and 30 kWh/m^2 per year, with negligible reduction (not exceeding 3% in the hottest climates) when cell temperature was taken into account. Visual comfort assessment was carried out using two typical metrics: Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP), comparing the performances of a photovoltaic glass with those of a commercial solar control glass and of a clear glass, acting as a reference. We found that the use of photovoltaic glass, independent of the location latitude, showed a significant increase in UDI values respect to clear glasses and performances comparable to solar control glasses. With reference to DGP, the use of photovoltaic glass allowed the reduction of occurrence of high DGP values (>0.45) of about 12–23%, depending on the location. Finally, we compared the annual energy production of building integrated photovoltaic cells to the annual use of electric energy for artificial lighting, finding that in most of the cases the annual energy production overcomes the amount of electric energy used for artificial lighting.

1. Introduction

According to the agreement of COP21, global warming should be kept below 2 °C by means of a massive reduction of greenhouse gas emissions (GHG). All new buildings will have to be nearly zero energy, as defined by the European Directive 2012/13/EU, i.e.

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buildings with very low yearly energy consumption, due to energy efficient design and to the use of renewable energy sources [1].

In this roadmap, a strong effort to the effective exploitation of innovative renewable sources (e.g. photovoltaics (PV), wind energy, etc.) could bring manifold advantages: firstly, the attenuation of foreign dependence but also a stimulus to a sustainable approach to development. Nowadays, PVs can be considered an established technology that can contribute significantly to lower GHG emissions and energy consumption in new buildings as well as in existing ones.

Building Integration of Photovoltaics (BIPV) is recognized worldwide as a relevant chance to integrate PV elements in the design of building components: BIPV has been identified as a suitable technology to improve building energy consumption performances and to reduce their ecological footprint. BIPV is a better alternative to Building Adopted PV (BAPV) systems, where PV panels are simply attached on exterior parts of building envelopes (on rooftops or facades). BIPV systems represent architecturally relevant components, active energy-producing units requiring the complex fulfillment of multiple requirements (aesthetic, economic, structural, acoustic, thermal, etc.) [2,3].

PV modules based on crystalline silicon cells (c-Si), still predominant on the market (with conversion efficiencies of 15% for polycrystalline and 20% for monocrystalline silicon cells) [4], are mostly rigid, opaque and flat. Such cells are not suitable for any integration requiring high transparency, even though several attempts have been made to encapsulate c-Si cells in laminated glass, by adopting a matrix of small panels with transparent spacing in between [5,6]. Despite this technology being difficult to integrate onto the architectural envelope, it is still one of the preferred solutions, for several reasons: lower costs, a consistent, long-lived mass production and, probably, the misleading consideration that c-Si cells outperform any innovative PV technologies in terms of efficiency, which is not always valid, e.g. in overcast sky conditions and when panels are installed on vertical facades. However, in many emerging technologies, high temperatures or sub-optimal tilt angles which reduce the efficiency of c-Si cells are less significant, ensuring good performances even when poorly irradiated or partially shaded [5].

These considerations in favor of innovative PV technologies can be even strongly supported by the fact that integration of PV modules into transparent components may be a much more effective choice, particularly in buildings with curtain-wall facades or large skylights. Clearly, in order to avoid affecting the occupants' visual comfort too much, good transparency (or, at least, semitransparency) becomes a fundamental requirement to comply with. In the last decades, a number of pioneering research investigations dealing with new PV materials has paved the way to the development of semitransparent, color-tunable, flexible, lightweight, robust and easily-processable PV technologies [7].

Among them, amorphous silicon solar cells (a-Si) [8] have currently reached the best laboratory efficiency of 10.2% [9]. This technology takes advantage of a much lower consumption of silicon with respect to first generation PVs, a lighter substrate (glass), a consolidated industrial process, based on plasma-enhanced chemical vapor deposition (PECVD) and, above all, its range of applications is widened by its peculiar semitransparency. Low-cost, lightweight and flexible a-si:H semitransparent solar cells (η = 3% and T_{vis} = 40%) have already been reported [1].

A tunable bandgap can be obtained in chalcopyrite-based solar cells, conventionally prepared by subsequent physical vapor deposition (PVD) processes. For example, 2 μm thick $Cu(In,Ga)Se_2$ (CIGS) solar cells have reached 20% conversion efficiency demonstrating a reliable and promising approach. In order to design semitransparent PV glazing, 1.2 μm thick CIGS solar cells were reported, with a conversion efficiency of 5.6% [10].

Organic PVs, which use thin, flexible layers of organic light-harvesting molecules to generate power, represent an interesting technology for BIPV, since efficiencies close to the best reported (11.5%) can be attained for semi-transparent devices. Nevertheless, their commercial use is still impeded by durability concerns [11,12].

Photoelectrochemical cells, based on mesoporous, semiconductive photoanodes and electrolytes containing suitably chosen redox couples (e.g. I_3^-/I^-, Br_3^-/Br^-) were named dye sensitized cells (DSCs) [13]. They have been considered, for a long time, as a promising technology for their possible use as an inherently semitransparent PV technology. Nevertheless, chemical degradation, leakage problems due to the use of liquid electrolytes, photochemical degradation of dyes and sealants still act as limiting factors affecting the reliability of this technology.

More recently, the emergence of perovskite-based solar cells has revolutionized the field of new generation PVs. They are easily-processable, solid-state high conversion efficiency solar cells, [14] most commonly based on hybrid organic-inorganic metal halides (ABX_3), with A = (CH_3NH_3, NH_2CHNH_2, Cs), B = (Pb, Sn) and X = Br, Cl, I enabling accurate tuning of bandgaps between ~1.2 and 3 eV [15–17].

A conversion efficiency of 20.1 ± 0.4% has been achieved by this recently developed technology [9]. Several strategies have been proposed in order to realize highly transparent perovskite cells. A typical device consists of a perovskite layer sandwiched between electron and hole transporting materials, respectively in contact with anode and cathode. The perovskite is typically thick enough to absorb all incident light, resulting in a device completely opaque. This technology has already been integrated in multifunctional photovoltaic/chromogenic devices [18]. Two main approaches have been reported to enhance cells transparency: making perovskite layers thinner, even if it leads to obtain brownish cells [19] or controlling the perovskite morphology, as to fabricate discontinuous micro-islands by tuning the physical parameters of the perovskite deposition process [20]. Such islands, when suitably designed, are invisible to the human eye and form neutral-tinted films, with minimal impacts on the spectral properties of light entering indoor. Recently, since such perovskite films with reduced coverage suffer from the contact between hole and electron transporting layers, which provides lower resistance (shunt) pathways, Hörantner et al. [21] improved this method by blocking these "shunting paths" via deposition of transparent, insulating molecular layers, via the use of an insulating octadecyl-siloxane molecular layer. This layer preferentially attaches to the exposed areas of electron transporting TiO_2, without obstructing the charge transport through the perovskite.

As it is quite predictable, BIPV not only affects energy aspects of the entire annual building energy balance, but also influences visual comfort concerns when it is applied to windows and other similar elements. According to Boyce et al. [22], the minimum acceptable glazing transmittance, in modern offices, lies in the range between 25% and 38%. This means that solar cells encapsulated in laminated glasses should overcome a threshold value in average transmittance for being considered suitable envelope technologies. Zomer et al. [23] investigated the balance between aesthetics and performance in building integrated first generation photovoltaics. Yang and Zou [24] investigated benefits and barriers to the diffusion of BIPV technologies. The manifold advantages and potentialities of BIPV technology were thoroughly investigated, such as the reduction of carbon emissions and social costs, environmental impact of constructions, significant reduction in land use for the generation of electricity and savings on electricity bills. They also highlighted that BIPV systems may result in a mere cost offset by replacing traditional building materials in architectural envelopes. As reported by Benemann et al. [6], compared to a stan-