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Energetic and visual comfort implications of using perovskite-based building-integrated photovoltaic glazings

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Abstract

Building integration of photovoltaics (BIPVs) has been recognized worldwide as a pivotal technology enabling the exploitation of innovative renewable energy sources in buildings, acting as electric power generators within the new framework of smart cities. Photovoltaic (PV) modules can be designed as relevant components of building envelopes, energy-producing units, fulfilling the multiple requirements of construction elements. Their integration in architectural glazings is still impeded by the inherent optical features of commercial solar cells, but also aesthetic, economic and social constraints, still acting as relevant barriers. In this roadmap, novel PV technologies could be effective drivers of a real change of paradigm. We have recently demonstrated that a coherent and exhaustive study of BIPV for semitransparent cells requires a "holistic approach", taking into account the complex fallouts of semitransparent modules on the energy balance, but also the full assessment of visual comfort benefits deriving from their integration in glazings. We have demonstrated that BIPV could offer manifold advantages: visual comfort effects comparable to commercially available solar control glasses and fair energy yield. Moreover, we found that in several cases the annual energy production overcomes the amount of electric energy used for artificial lighting.

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Keywords: Building-integrated photovoltaics; energy performance; energy simulation.

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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 (GHG) emissions. The building sector represents between 30% and 40% of the demand in final energy in developed countries, dramatically affecting GHG emissions and climate change. In order to mitigate this huge environmental impact, net zero energy buildings have been conceived, i.e. buildings showing annual zero energy balance. The Directive Energy Performance of Buildings, approved in 2002 and recast in 2012, requires that new buildings in the EU will have to produce the consumed energy to a very large extent employing renewable sources of energy [1]. At the same time, the traditional scheme of the electric grid, powering industrialized countries worldwide, based on its rigid basic components (generation, transmission and distribution of electric power), is a complex and fragile system, neither capable of storing electric energy nor of matching instantaneous changes of demand and offer. In such a framework, it is not possible to face the intrinsic intermittency and fluctuation of delocalized renewable sources. Re-engineered electric grids, named “smart-grids”, and so on, can use digital information to cope with the deployment of stochastic renewable sources. In this roadmap, moving from a fossil fuel economy to an electricity economy, a strong effort to the effective exploitation of innovative renewable sources (e.g. photovoltaics (PV), wind energy, etc.) could bring manifold advantages: the attenuation of foreign dependence and a stimulus to a sustainable approach to development. Sunlight represents an abundant, inexhaustible and equally distributed renewable source of energy. 90 PW of radiant power is received continuously on the planet’s surface: a far larger amount of energy respect to global rate of energy consumption: 17.2 TW in 2014. The amount of energy we can get from the average solar power striking the surface of Earth (170 Wm^{-2}) depends on the harvesting capacity of our technologies. In the same year, PV global capacity was almost 180 GW. With hydroelectric and wind renewable sources, they reached 20.6 % of world energy demand. [2]. 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.

2. Open issues of BIPVs

Building Integration of Photovoltaics (BIPV) represents a relevant chance to improve building energy performance and to reduce their ecological footprint, especially in the future scenario of the smart-grid, promoting buildings to the role of small, delocalized power plants and simple energy consumers to the role of aware “prosumers”. BIPV is a better alternative to Building Adopted PV (BAPV) systems, that are simply attached on exterior parts of architectures (on rooftops or facades). BIPV systems represent architecturally relevant components, capable of producing electric energy but also fulfilling complex requirements of building envelopes (aesthetic, economic, structural, acoustic, thermal, etc.) [3,4]. BIPV manufacturers have to face several barriers: the more convenient price of BAPV systems for roofings and opaque facades, the persistent lack of awareness of designers and consumers, the underestimation of the BIPV market in favour of “traditional” BAPVs. The convenience of BAPVs is also linked to the almost 7-fold drop of the PV module price in the last decade, mainly due to the 10-fold increase of the Chinese production. In 2014, [2]. According to IEA, only considering the leading industrial countries, BIPVs could even exceed an energy production of 1 TWhp. The complex design of these multifunctional architectural components requires both the consideration of regulation and technical constraints and a wide expertise on technical and aesthetic issues. Conversion efficiency and peak power production are relevant figures of merit but fail in envisaging the real energy production without taking into account, precisely, specific location, exposure and climate conditions, temperature coefficient or yearly degradation. For instance, shading due to chimneys or other obstructions could heavily affect energy production in some cases (c-Si solar cells) rather than in others, performing better even when partially shaded (a-Si solar cells). Expectedly, the BIPV market is dominated by BAPV systems for roofings and facades. The most difficult challenge is represented by the integration of PV systems in architectural glazings. Homogeneous, highly transparent and multifunctional PV technologies could act as relevant drivers towards the diffusion of BIPV for architectural glazings, overcoming the multiple barriers still impeding its widespread diffusion: several research groups have been attracted by this open issue. Some of the authors have proposed dynamic tintable glazings acting simultaneously as semitransparent PV systems and smart solar control devices [5,6]. The slow diffusion of BIPV is also a technological problem, especially with reference to semitransparent PV technologies, which require special considerations, pointed out hereafter. Zomer et al. [7] investigated the balance between aesthetics and performance in building integrated c-Si cells. Yang and Zou [8] investigated benefits and barriers to the diffusion of BIPV technologies, like reduction of carbon emissions and social costs, environmental impact of constructions, attenuation of land use for the generation of electricity, savings on electricity bills. They also highlighted that BIPV systems. As reported by Benemann et al., BIPV of silicon cells may result in a mere cost offset on building materials for architectural envelopes, i.e. an additional cost of about 350-500 $\$/m^2$ [9]. The development of reliable, multifunctional devices could represent an effective chance to overcome persistent market barriers impeding the diffusion of BIPVs.

3. Photovoltaic technologies for building integration

Silicon is one of the most abundant elements on Earth. PV modules based on silicon wafer crystalline cells (c-Si), are based on the working principle of a doped p-n semiconducting junction. c-Si cells are still predominant on the market but are mostly rigid, opaque and flat. The market share of c-Si modules has reached 90% in 2014: a consistent increase respect to 2009 (+10%) due to the slow increase of other emerging PV technologies [2]. Their typical conversion efficiencies, 15% for polycrystalline and 20% for monocrystalline cells, make them reliable mainly for ground mounted and roofing applications. Such cells are less suitable for any integration requiring high transparency, even though several efforts have been made to obtain facades encapsulating c-Si cells in laminated glasses, by properly setting the mutual distance between the cells [9,10], with a resulting pattern of shades that can cause visual discomfort in several cases. Despite this technology is the most difficult to integrate into architectural glazings, since its output is affected by even partial shading, non optimally tilted installation and low irradiation levels, it is still one of the preferred solutions. This contradictory trend is based on the misleading consideration that c-Si cells show high conversion efficiency, outperforming thin-film PVs and other innovative PV technologies.

The above 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 too much occupants' visual comfort, good transparency (or, at least, semi-transparency) becomes a fundamental requirement to comply with. In the last decades, a number of research investigations dealing with novel PV materials paved the way to the development of semitransparent, color-tunable, flexible, lightweight, robust and easily-processable PV technologies.

Moreover, in newly conceived PVs, the efficiency decrease due to high temperatures or to sub-optimal tilt angles is often less significant than in silicon-based PV cells, ensuring good performances even when poorly irradiated or partially shaded [10]. Among them, amorphous silicon solar cells (a-Si) in the so called p-i-n configuration were first fabricated by Carlson and Wronski in 1976 [11], and have currently reached the best laboratory efficiency of 10.2% [12]. This technology takes advantage of a much lower consumption of silicon respect to first generation PVs, a consolidated industrial process, based on plasma-enhanced chemical vapor deposition and, above all, its range of applications is widened by its peculiar semitransparency. According to precise theoretical investigations, the ideal bandgap should be 1.5 eV and it has been observed that the conversion efficiency of hydrogenated a-Si (a-Si:H) solar cells decreases when the thickness of layers decrease. Thus a convenient trade-off has to be found between transparency and average transmittance. A thickness of 200 nm or less of the i-a-Si:H layer has been found to maximize transparency as well. Low-cost, lightweight and flexible a-Si:H semitransparent solar cells (η= 3% and T= 40%) have already been reported [13]. A tunable bandgap can also be obtained in chalcopyrite-based solar cells, conventionally prepared by subsequent physical vapor deposition 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. Several efforts have been made to fabricate highly efficient ultrathin (thickness < 1μm) chalcopyrite-based solar cells, though a continuous drop of conversion efficiency was observed as a direct consequence of a decrease in the absorber thickness. To design semitransparent PV glazings, 1.2 μm thick CIGS solar cells were reported, with a conversion efficiency of 5.6% [14].

DSCs or Grätzel cells represent a class of promising photoelectrochemical cells, based on mesoporous, semiconductive photoanodes and electrolytes containing suitably chosen redox couples (e.g. I_3^-/I^-, Br_3^-/Br^-). They have raised attention worldwide, for a long time, for their possible use as an inherently semitransparent PV technology, good conversion efficiency even when fairly irradiated and up to high angle solar incidence. Moreover, they show potentially low fabrication cost and simple production process with lower energetic cost and energy payback time respect to consolidated TF technologies: Parisi et al. showed that an energy saving in the range between 48% and 66% and a reduction of CO_2 emissions in the range between 49% and 76% are achievable employing the DSSC module for photovoltaic installation [15]. A few demonstration projects have shown the feasibility of their use for building integration, like the EPFL's Campus in Lausanne[16]. Maximum Cell and module efficiency reported in literature represent encouraging figures of merit for this PV technology: 11.9 ± 0.4 % in small cells and 8.8 ± 0.3 for submodules [12]. 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, affecting durability [2]. Stability of DSC modules is strongly related to the encapsulation process, as reported by Hagfeldt et al. [17].

On the other hand, Organic PVs, with record cell efficiency of about 11.5% [12], represent an interesting, innovative technology for the nano-exploitation of material properties, potentially low production costs and their tunable semitransparent aspect. They show simple devices, based on bulk heterojunction architectures employing, generally, polythiophenes as electron donors and fullerenes as electron acceptors, but also all-polymer cells have been demonstrated [18]. Visibly transparent polymer solar cells by solution processing have been reported by Chen et al. with maximum transmittance of 66% at 550 nm and 4% power-conversion efficiency. Nevertheless, their commercial use is still impeded by stability concerns, affected by light irradiation, temperatures and contamination of materials [19,20]. Highly transparent organic cells are indeed potential players for BIPV applications for their tunable colors and level of customization [21-23].

The recent raise of perovskite-based solar cells has quite revolutionized the field of new generation PVs. They are easy-processable, solid-state high conversion efficiency solar cells [24], based on methylammonium lead trihalides (CH_3NH_3-PbX_3), with X= Br, Cl, I enabling an accurate tuning of bandgaps. Also the alkyl group CH_3 can be suitably replaced, with the same purpose [25-27]. Environmental issues have also activated the replacement of Pb with other materials [28]. A conversion efficiency of 20.1±0.4% has been achieved by this recently developed technology, as reported by Green et al. [12] Several strategies have been proposed in order to realize highly transparent perovskite cells. The most simplified device consists of a perovskite layer, devoted to light absorption, sandwiched between electron and hole transporting materials, respectively in contact with anode and cathode. The perovskite is typically thick enough to absorb over the entire visible spectrum (bandgap 1.55 eV), rendering the device completely opaque, but also allowing the fabrication of very thin layers. The energy levels of the materials involved can determine high open circuit voltages, overcoming 1.0 V. Energy payback times of less than 3 months have been estimated for this cells, though some stability concerns of perovskite still impede commercial diffusion and enhanced sealing is required [29]. Starting from these remarks, two main approaches have been reported to achieve high cells transparency: making perovskite layers thinner, which inevitably leads to obtain brownish cells [30] and controlling the perovskite morphology, as to fabricate discontinuous micro-islands by opportunely tuning the physical parameters of the perovskite deposition process [31]. Such islands, when suitably designed, are invisible to the naked eye and eventually contribute to the formation of neutral-tinted films, with minimal impacts on the spectral properties of light entering indoor. Moreover, since perovskite films often suffer from pinholes and the resulting contact between hole and electron transporting layers provides lower resistance (shunt) pathways, Hörantner et al. 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 [32].

4. Multifunctional devices for building integration

As it clearly appears, photovoltaic conversion efficiency cannot be the basis of a "one-fits-all" approach when choosing a suitable semitransparent BIPV technology: in fact, apart from module efficiency, several other aspects should be taken into account: local climate conditions, presence of shadings (trees or overlooking buildings), façade exposition, solar path. Geographical conditions may affect PV temperature coefficient and the real amount of irradiance (diffuse or direct) and, eventually, generated electric power, apart from peak power production of the selected PV technologies, generally measured in Standard Test Conditions. BIPV affects not only the entire annual building energy balance, but also visual comfort concerns when applied to glazings. Boyce et al. [33], verified that in modern offices glazings must report a transmittance range spanning between 25% and 38%. Then, solar cells included in glazing units or encapsulated in laminated glasses have to overcome a minimum threshold value in transparency for being considered suitable for envelope technologies. Transparency is not the only parameter affecting comfort perception indoor: also the resulting color of glazings hosting PV technologies plays its role: for instance, grey is associated with neutrality in the psychology of human perception [10]. Cells showing red, brown or yellow tints could be hardly integrated in windows. Transparency and color of glazings modify and filter daylighting passing indoor. As a consequence, one cannot estimate the suitability of a BIPV technology without considering, on a yearly basis, effects on visual comfort figures of merit, like Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP) as well as the spectral quality of light. More recently, Chae et al. [34] suggested a procedure to evaluate the energy performance of buildings incorporating BIPVs, considering not only the electrical characteristics of PV cells, but also thermal and optical behavior and the consequent implications on building energy performance. They found that the maximum electric energy generation using a-Si:H cells could range from 30 kWh per year to 62 kWh per year, depending on several parameters (type of PV cell, site location, exposition). Oliver et al. [35] studied the influence of building integrated semitransparent solar cells on heating, cooling and lighting loads and electricity generation, considering parameters like Window-to-Wall-Ratio (WWR) and cells average visible transmittance (T_{vis}). They proposed a comparison with conventional solar control glasses compliant with local technical standard, eventually finding that semitransparent BIPVs on larger windows (WWR>33%) could provide a promising energy saving potential between 18% (WWR=33%) and 59% (WWR=88%) compared to regular glass. Apart from this, further considerations are required in order to choose the ideal PV technology according to the building shape and the depth of rooms hosting semitransparent BIPV glazings. Building typologies indeed matter. In fact, the amount of electric power for lighting in deep spaces could frustrate the energy advantages deriving from the energy yield of PV glazings.

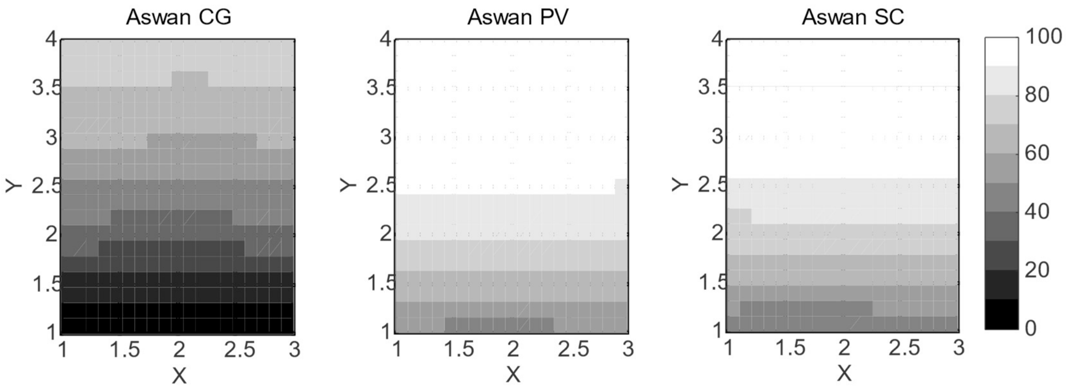

Figure 1. Spatial distribution of the percentage of time during the year in which the Useful Daylight Illuminance (UDI) is within comfort limits for the selected locations with a typical office window (WWR = 32%). CG = clear glass; PV = transparent perovskite-based photovoltaic; SC = commercial solar control film.

We recently observed that for spaces deep up to 5m and a WWR of 32%, the annual energy yield can be comparable or higher than the energy spent for artificial lighting [36], (Table 1) in locations having a lower latitude than Rome. In this work, we adopted a parametric approach to find out the ideal geometric configuration of building integrated semitransparent perovskite films, adopting specific tools (Daysim and Matlab). We used electro-optical features of laboratory cells as viable inputs for simulations, as already done previously, to assess visual comfort effects due to building integrated photoelectrochromic technologies [6,37,38]. Such models were used in the hypothesis of different climatic conditions (London, Brindisi and Aswan). In each location, we studied two types of test-rooms, equipped with glazings with a different size (WWR= 19% and 32%). 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. For smaller windows, with WWR=19%, PV glazings improved the performances respect to clear glasses, as all the receptors had UDI at least equal to 70% and, in most of the cases, well above, showing results comparable to a commercial solar control film. In office test-rooms (WWR=32%), the presence of PV glass shifted UDI values towards the top: in Brindisi 67% of receptors were in the “excellent” range (only 8% when using clear glass); the most relevant results were achieved in Aswan, where the receptors in the “excellent” range reached 75%. (Figure 1)

With reference to DGP, the use of photovoltaic glass allowed the reduction of occurrence of high DGP values (>0.40) of about 12–23%, depending on the location. (Figure 2) The PV glass outperformed both solar control glass and clear glass with only 12% work hours above the DGP limit, when considering an office test-room.

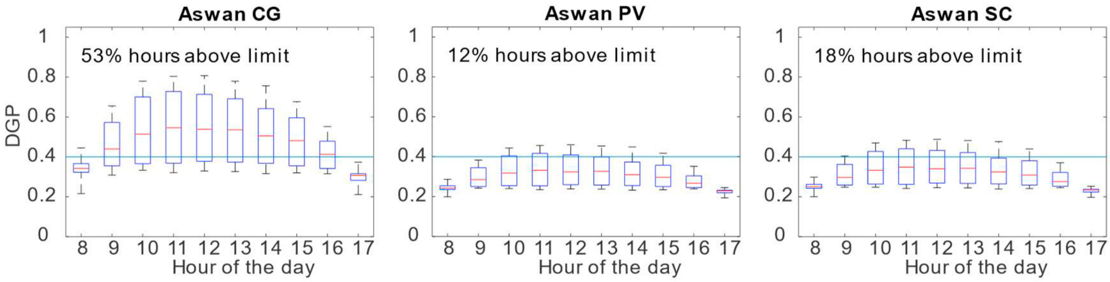

Figure 2. Boxplot of the Daylight Glare Probability (DGP) yearly distribution for the selected locations as a function of working hours for a typical office window (WWR =32%). Box represents 1st and 3rd quartiles with the median given by the red horizontal line. Whiskers correspond to minima and maxima in each set. CG = Clear glass; PV = Transparent perovskite-based photovoltaic; SC = commercial solar control film.

Table 1. Use of electric lighting for offices having strip windows with a WWR=32%. Load is meant as the annual electric lighting energy load in the test room; Yield is the Annual Electric energy yield (including temperature effect).

Location	Type of glazing	LOAD [kWh/yr]	YIELD [kWh/yr]	Yield/Load [%]
	Clear Glass	78	-	-
Brindisi	Solar control glass	108	-	-
	PV glass	118	129.0	109.3
	Clear Glass	136	-	-
London	Solar control glass	198	-	-
	PV glass	200	82.40	41.2
	Clear Glass	52	-	-
Aswan	Solar control glass	68	-	-
	PV glass	68	143.40	210.9

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 raise was taken into account. Respect to clear glass, either solar control glass and PV glass showed a slight increase in energy consumption, due to the occurrence of low illuminance sensor points, as more evident in London. On the contrary, in Aswan, the values almost coincided. In Aswan and Brindisi the energy yield exceeded the yearly energy consumption for artificial lighting (143.40 kWh/yr and 129.0 kWh/yr, respectively, as shown in Table 1). We eventually demonstrated that the reported perovskite-based PV technology offers a double advantage if building integrated. In fact, it not only produces an annual amount of electric energy which is comparable to that obtained by using commercial a-Si cells, but also can be exploited as solar control films for glasses, effectively shielding undesired solar gains thus allowing energy saving and the achievement of higher levels of visual comfort indoor. This can be considered indeed a multifunctional device for solar control and electric energy generation.

In a more recent work, we also considered the effects of this technology in a real case study, a large, recently designed office building, located in Southern Italy (Bari, Apulia). The software EnergyPlus v. 8.6 was adopted, in order to take advantage of its detailed output in terms of yearly exterior surface irradiation. In this case, we verified the multiple effects of building integration of perovskite photovoltaic glass in the facades. We showed that use of semi-transparent perovskite-based PV glazing reduces the overall passive energy balance by 4%. In addition, 27.9 MWh/yr can be obtained, resulting in a 15% net energy reduction compared to the reference condition. Adding opaque PV shades predictably reduces the energy yield of the PV glazings (which drops to 16.6 MWh/yr), but returns an additional 25.7 MWh/year energy yield which combined to the passive benefits, returns a 22% net energy reduction compared to the reference case.

4. Conclusions

In this paper, we have tried to define the current state of art of research dealing with BIPVs, focusing especially on research trends in semi-transparent PV technologies, of particular interest for integration in architectural glazings. We have reported the results of recent studies, demonstrating the utility of some recently developed PV technologies in terms of energy production and energy savings as well. The application of a semitransparent PV film in “Face 2” of a common double glazing unit, in fact, not only requires accurate reflections about façade irradiation, optimum exposure characteristics, but also special considerations about the achievement of satisfactory levels of occupants’ visual comfort. In fact, more considerations concerning the spectral quality of natural light penetrating indoor are required, apart from merely calculations of the attainable electric yield. By adopting a multi-software, more complex approach, we could deduce that a perovskite-based PV film, for its optical characteristics, can be assimilated to a commercial film for solar control. But, in addition, it was possible to obtain an annual energy output comparable to that obtained by using stabilized second generation TF technologies. In this case, we carried out an extended study, evaluating the effects on the annual energy balance, noting a not negligible reduction in the annual air conditioning cost, in the given location. These considerations support the thesis that the complex study of building integrated semitransparent PVs in glazings requires an inevitably multidisciplinary effort for a “holistic approach”.

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