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Energy performance of building-integrated electrochromic and photovoltaic systems

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Abstract. Innovative nanotechnology-based devices can offer multiple advantages in terms of renewable energy harvesting as well as energy saving in buildings. Among the technologies that can be used in transparent and semi-transparent building envelopes, neutral-colored perovskite-based heterojunction photovoltaic (PV) cells and solid-state electrochromic (EC) devices may play a pivotal role. These classes of devices have proven to offer significant benefits in terms of energy saving and enhancement of indoor visual comfort. In this work, the two types of technologies will be compared by considering two similar buildings equipped with glazing embodying such devices, with reference to specific climate conditions.

1. Introduction

The latest version of the European Directive on the energy performance of buildings (Directive 2018/844/EU, amending the existing 2010/31/EU) [1] aims at accelerating the renovation of existing buildings, towards a fully decarbonised building stock by 2050. The construction sector is responsible for 40% of primary energy consumption [2] in the most developed countries. To achieve this epochal result it will be necessary to change energy consumption habits but also to adopt newly designed technologies, capable of reducing process costs, use of raw materials as well as maintenance operating costs, against a significant performance increase compared to materials and devices already available in the state of the art. In this work, we propose to analyse and compare the benefits deriving from the building integration of innovative semi-transparent photo-voltaic (PV) systems and solid-state electrochromic (EC) glass within transparent building envelopes.

Despite the universally recognized importance of the integration of photovoltaics in buildings, still very few technologies are ready to be embodied in glazed components above all due to low values of the solar factor, preventing a sufficient penetration of daylighting indoor. Several PV devices allow to create highly transparent systems although at the price of a drastic reduction in conversion performance. In particular, some semi-transparent PV systems already on market embody second-generation thin films, based on amorphous silicon (a-Si) or on Cadmium-Telluride (CdTe) p-n junctions. The new generation of PV technologies has been very recently revolutionized by the appearance of perovskite-based solar cells, which has attracted the attention of a large number of research groups around the world. In a few years, this new technology has exceeded the PV conversion efficiency of 20% in laboratory tests, with an interesting growing trend [3-5]. Some researchers, instead of reducing the thickness of the device which, as already stated, entails significant performance reductions in terms of PV conversion, tried to control the morphology of perovskite, obtaining micro-islands of full thickness, but with a sufficiently small transverse dimension that cannot be perceived by the human eye. In this way the suitable tuning of deposition parameters allows to accurately design the coverage ratio of micro islands compared to the transparent surface [6,7]. Afterwards, several works have appeared, dealing



with benefits resulting from the building integration of similar devices in façades, in terms of energy performance and of visual comfort indoor, as well.

On the other hand, EC smart windows, according to C. G. Granqvist, can be considered a “green nanotechnology” [8,9], able to regulate the throughput of visible light and solar radiation across a glazing, by suitably tuning its dynamic behaviour, with significant benefits in terms of energy saving and visual comfort enhancement. In a typical EC device, transparent conductive substrates are present, an interposed electrolyte, in a liquid, solid or gel phase, and one or two EC materials. These materials undergo reversible changes of their optical absorption upon electron insertion in their structure (in the case of cathodic EC materials, or extraction, respectively, in the case of anodic EC materials) and upon simultaneous intercalation of charge-balancing small ions (or de-intercalated, respectively) [10]. The above mentioned architecture depicts the typically used “battery-like” EC device structure. Some of the authors have recently proposed a new solid-state electronic technology and have initiated studies concerning the consequent benefits of their integration into building facades [11,12]. Such devices were fabricated on a single substrate, made of glass or flexible plastic, with a rather simple architecture compared to smart windows already on the market. This simplified architecture allows, on the one hand, to envisage lower production costs and, on the other hand, the whole process can be carried out at room temperature, thus reducing costs and environmental impacts. The authors also investigated the benefits of solid-state EC devices on visual comfort: the assessments were carried out in terms of Useful Daylight Illuminance and Daylighting Glare Index. The visual comfort assessments reported significant improvements due to innovative solid-state EC devices: on a yearly basis, 80.2% of hours were in optimal illuminance conditions (42.4% when a clear glass is used). In this work, a test room was studied, that can be considered part of a large multi-storey office building located in Rome. The objective of the study will be to compare the overall energy consumptions resulting from the integration of semi-transparent PV systems and solid-state EC systems. The goal is to achieve a critical comparison between the two technologies, showing the benefits that could arise in a “cooling dominated” climatic context, like the Mediterranean one.

2. Methods

2.1. Fabrication and characterization of semitransparent solar cells

Perovskite-based neutral colored semi-transparent cells [6] at the basis of this study were prepared following the procedure described by Hörantner et al. [7]. After cleaning and patterning FTO/glass substrates, these were coated using a compact TiO₂ n-type layer; then, suitably dewetted perovskite micro-islands were deposited by spin-coating. Afterwards, a shunt-blocking layer made of Octadecyl-trichloro-silane was applied to improve the device performance and reduce “shunt paths”. The spiro-OMeTAD (2,2',7,7'-Tetrakis(N,N-di-p-methoxyphenylamine)-9,9'-spirobifluorene), acting as a hole-transporting layer was then deposited, before completing the device by laminating a flexible and transparent Nickel micro grid on top. Measurements of PV performance of the solar cells were carried out at standard test conditions (25 °C under simulated AM 1.5 sunlight giving 1000 W/m² equivalent irradiance under a solar simulator).

2.2. Fabrication and characterization of solid-state, single substrate EC devices.

Solid-state devices used in this work were fabricated on a single glass substrate, with a simplified architecture, embodying only one cathodic EC material (substrate/Indium Tin Oxide/Tungsten Oxide/Nafion/Indium Tin Oxide). The devices underwent full electro-optical and electrochemical characterization (transmittance and kinetic spectra, cyclic voltammetry and chrono-amperometry measurements) as reported in [11,12] and the resulting figures of merit were adopted in the simulations described in the following paragraph.

2.3. Simulations of building integrated devices

All the analyses were carried out using EnergyPlus v. 8.9 [13], a free simulation tool, developed by the U.S. Department of Energy's Building Technology Office, for modeling thermal loads and performing energy analysis of whole buildings or with reference to single thermal zones. The modelled test room had a rectangular area of 20 m² (4 m by 5 m), with a net height of 3 m, representing a typical

office unit (Figure 1), as already done in other works. Fenestration, located on the smaller side of the test-room, was assumed to have thermal–optical properties of a double-pane glazing unit (4 mm-clear glass/16 mm-argon gap/ low-e coated 4 mm-clear glass), acting as a baseline model, ideally representing existing building conditions, but fulfilling current regulations ($U= 1.73 \text{ W/m}^2\text{K}$, $T_{\text{vis}}= 76 \%$, $\text{SHGC}= 0.751$). The only vertical opaque wall subject to heat exchange (i.e. the one embodying the glazing systems) was designed with U_{factor} of $0.35 \text{ W/m}^2\text{K}$ (with air film), whereas all the other surfaces were considered adiabatic. Heating and cooling energy consumption were estimated adopting an “IdealLoadAirSystem”, providing both the heating and cooling energy required to meet the temperature set-points, provided by the corresponding schedules. A constant COP of 3 was assumed to convert such values into electrical energy. The room was supposed to be occupied by two persons, and ventilation rate was assumed to be $0.0125 \text{ m}^3/\text{s}$ per person. Infiltration rate was expressed in terms of flow per surface area, and set equal to a value of $3 \cdot 10^{-4} \text{ m}^3/(\text{s} \cdot \text{m}^2)$. Starting from this “reference case”, rooms equipped with PV glazing and EC devices were also simulated. The analyses were carried out by taking into account actual (experimental) performance of devices. Thermo-optical properties of PV window were: $U= 1.73 \text{ W/m}^2\text{K}$, $T_{\text{vis}}= 31.1\%$, $\text{SHGC}= 0.34$, while for EC window were: $U= 1.73 \text{ W/m}^2\text{K}$, $T_{\text{vis}}= 29.1\%$, $\text{SHGC}= 0.32$. As to PV cells, the conversion efficiency of the cell was related to radiation intensity, using a linear behaviour. Irradiance values adopted in the simulation were retrieved from the same weather file (.epw) used in EnergyPlus simulations. The electrochromic system was controlled according to the available illuminance available in the sensor point assumed on a desk inside the office (“MeetDaylightIlluminance” strategy, set at 300 lux). Three different values of window to wall ratio (WWR) were adopted (21%, 42% and 80%), to investigate the effect of glazing size on the energy performance, on an annual basis. Detailed simulations were carried out with reference to Rome (Mediterranean climate, Csa according to Koppen-Geiger classification). Simulations were made for each value WWR value and for any facade exposure (North, East, South and West).

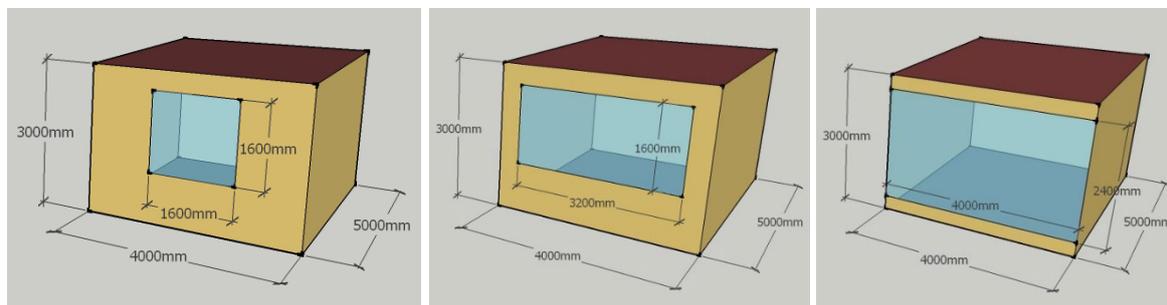


Figure 1. 3D models of the test-office analyzed. Left: Low size window (WWR=21%; Middle: Medium size window (WWR=42%); Right: High size window (WWR=80%)

3. Results and discussion

The production of electricity for each façade was evaluated using the characteristics of the semi-transparent devices described in the previous paragraphs, taking into account both the dependence of the PV efficiency parameter on the temperature of the substrate and of the relative position of sun.

Table 1. Annual PV yield, expressed in $\text{kWh/m}^2\text{yr}$, with reference to the room surface unit. PV Yield [$\text{kWh/m}^2\text{yr}$]

	Window surface	Exposure			
		E	W	N	S
Large	9.6	5.0	10.6	1.0	12.3
Medium	5	2.6	5.5	0.5	6.4
Small	2.5	1.3	2.8	0.3	3.2

Data were reported in **Table 1**, showing that ideal exposures for these devices, with reference to the context of the city of Rome, are South and West. At the same time, the absolute value of PV generation increases with WWR values. **Figures 2, 3** and **4** clearly show that the yearly energy consumption

(lighting, heating and cooling) within the office increases as a function of the WWR and according to the façade exposures. A common trend can be observed, showing an increase in the energy consumption (lighting, heating and cooling) within the office as a function of the WWR: such increase is more significant in the “reference window” and is attenuated both using the PV glass (also acting as an effective solar control film) and in the room equipped with EC window, which takes advantage of the dynamic management of its spectral properties.

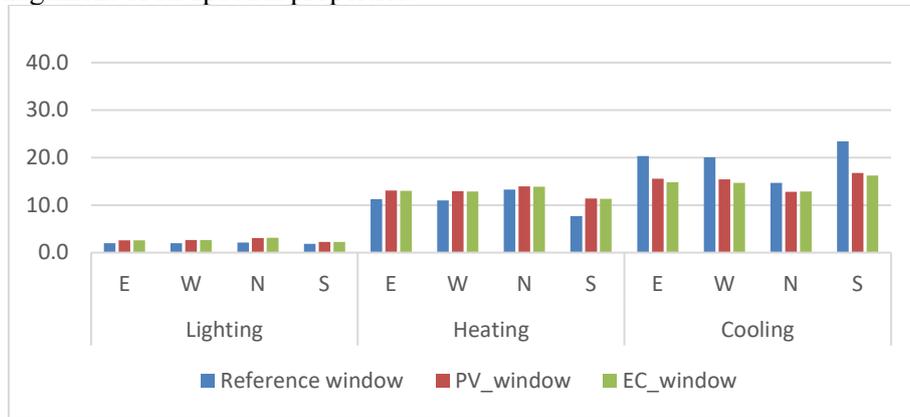


Figure 2. Energy uses (lighting, heating and cooling) in the test room with small glazing surface (WWR=21%), according to exposures.

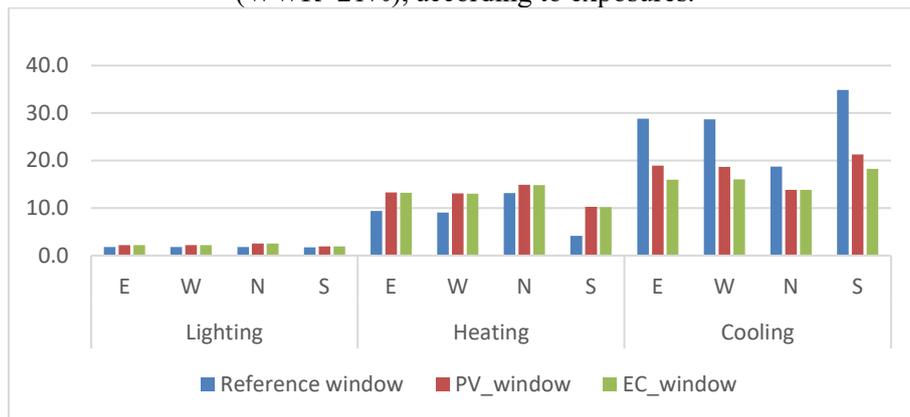


Figure 3. Energy uses (lighting, heating and cooling) in the test room with medium glazing surface (WWR=42%), according to exposures.

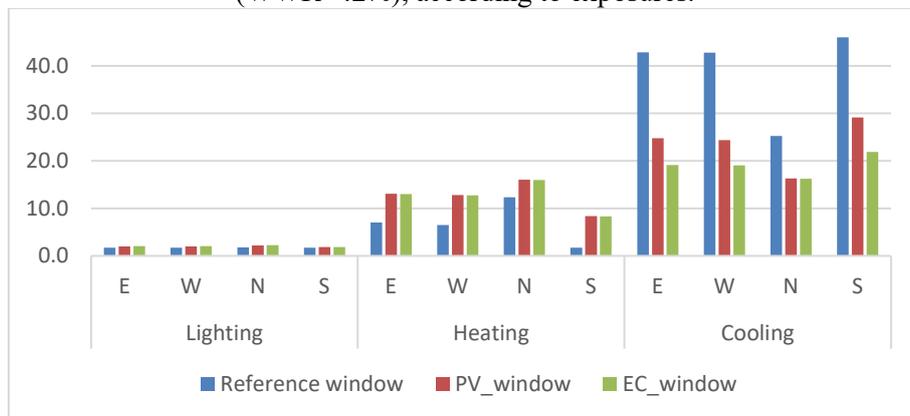


Figure 4. Energy uses (lighting, heating and cooling) in the test room with large glazing surface (WWR=80%), according to exposures.

In all the analyzed cases, the main item of energy consumption is related to summer cooling, due to the latitude and weather conditions in the city of Rome. The heating energy is relatively low and influenced by the amount of solar gains due to direct and diffuse irradiance but also to the scheduled values of

outdoor air flow rate infiltration. Windows equipped with PV and EC glazing show higher heating consumption due to the significant reduction of their SHGC, associated to their inherent optical properties. For similar reasons, energy consumption for lighting undergoes slight (and similar) increases when PV or EC façades are adopted.

When WWR= 42%, the use of technologies capable of cutting out undesired solar radiation results in high rates of energy saving for cooling. In fact, during the cooling season, the East, West and South façade show high deviations in energy consumption, compared to the reference case: the energy saving for summer air conditioning reaches 40% in the case of PV glass and 48% using EC glazing with WWR=80% (**Figure 3**), for the South exposure. The variation between the two technologies is in the order of 15%, in favor of the EC technology, due to the greater effectiveness of its dynamic shielding feature.

The magnitude of these differences is amplified when considering the maximum value for WWR (80%): in this case, the energy uses for cooling are halved in the PV glass and are cut by 41% using EC smart windows. The increase in consumption for artificial lighting observed when PV or EC glass is adopted is by far covered, in absolute terms, by energy saving observed for cooling in the air conditioning season. A similar argument can be made for the energy consumption relating to the heating period: the reduction of the solar factor in PV and EC glazing excludes the chance of using free solar gains during the winter season (**Figure 4**).

The evaluation of the total annual energy consumption, referring to the unit of surface area, is shown in **Table 2**. Unlike previous plots, it includes the calculation of the annual electricity production due to the PV film, considered with a negative sign. In this case, the PV glazing even outperforms the EC one, thanks to the PV conversion, whose effect is higher on South-facing and West-facing exposures. It is interesting to observe that by including PV yield in calculations, expositions with the best solar irradiation (S and W) return overall energy needs that become substantially independent of windows surface.

Table 2. Yearly energy uses, including electricity generation of PV glazing.

Small window (WWR = 21%)	Net yearly energy uses [kWh/m ² yr]			
	<i>E</i>	<i>W</i>	<i>N</i>	<i>S</i>
Reference window	33.6	33.1	30.1	33.0
PV_window	29.9	28.3	27.1	27.2
EC_window	30.5	30.3	29.9	29.9
Medium Window (WWR = 42%)	<i>E</i>	<i>W</i>	<i>N</i>	<i>S</i>
Reference window	40.0	39.5	33.7	40.8
PV_window	31.8	28.4	30.8	27.1
EC_window	31.4	31.3	31.3	32.1
Large Window (WWR = 80%)	<i>E</i>	<i>W</i>	<i>N</i>	<i>S</i>
Reference window	51.6	51.0	39.3	56.8
PV_window	34.8	28.7	33.6	27.0
EC_window	34.2	33.8	34.4	32.1

When all energy consumption is taken into account, the maximum saving achievable in one year reaches 50% in the office with PV glazing and 40% in the office equipped with the EC technology, for WWR=80%, on the South-facing exposure; with the same WWR value, on the West-facing façade, the savings are 56% with PV glazing and 44% with EC glazing. In similar conditions, further considerations about daylighting uses and visual comfort may be useful to evaluate which technology can best meet the required performance requirements.

4. Conclusions

The present work compares two innovative technologies for transparent envelopes, in the climatic context of the city of Rome, referring to an office building with different WWRs and all the exposures. The results obtained offer an interesting and unprecedented comparison between the perovskite-based PVs and a recent architecture for solid-state EC glazing. In both cases, these are devices on which the authors have carried out experimental scientific work in recent years and the experimental data were used as a basis for this study. Results obtained show the effectiveness of both the technologies to achieve really outstanding energy saving, especially on the West and South-facing façades, increasing with WWRs. The amount of energy saving is higher when EC glazing is chosen, but if the PV conversion efficiency achievable in PV glazing is taken into account, the overall energy performance rewards the PV technology, that even outperforms EC glazing.

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