RESEARCH

EVALUATION OF PV POWERED SWITCHABLE GLAZING TECHNOLOGIES IN TERMS OF THEIR SUITABILITY FOR OFFICE WINDOWS IN MODERATE CLIMATES

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ABSTRACT

In the search for façade solutions that meet requirements for energy efficiency and office space use comfort, it seems promising to apply a combination of photovoltaic (PV) technology with switchable glazing. It is believed that the merging of these two technologies might benefit the cooperation between regulated solar protection and energy efficiency. This article provides a design outlook on the use of PV-EC, PV-SPD, and PV-LCD technologies in terms of their utility for office buildings in moderate climates. This study concerns thermal, optical-visual, energetic, and technical issues, and a comparative method was applied. Based on current scientific research, the results of the analysis were juxtaposed with the requirements of the office working environment: natural lighting, thermal protection, glare protection, privacy control, energy efficiency, and technical reliability. The juxtaposition of these aspects revealed the advantages and disadvantages of a given solution from an architectural point of view. PV-EC technology in a side-by-side system was found to be the most appropriate solution and the results may be applied to make preliminary design decisions.

KEYWORDS

PV technology, switchable glazing, office buildings, PV windows, energy-efficient architecture

1. INTRODUCTION

The building sector consumes more than 50% of the world's energy production (Behling 2000). As the most numerous non-residential buildings, office buildings are a strategic group of facilities that would benefit from energy-saving solutions. Apart from the energy-consumption aspects, important issues comprise the comfort of use, including thermal and visual elements experienced by an office worker who represents the most populous professional group globally (Złowodzki 1992). These aspects are of significant concern in all recognized pro-ecological building certification methods, including BREEAM and LEED (Altomonte et al. 2017; Gou et al. 2012; Laxman et al. 2019). The need to consider these issues is also emphasized in the research on the NZEB (Sańka et al. 2019) and ZEB (Zaikina et al. 2019) buildings.

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Designing pro-ecological and energy-efficient architecture in terms of bioclimatic conditions is particularly interesting in moderate climate zones. Depending on the season, both heating and cooling needs arise in such areas (Boemi et al. 2016; Lok et al. 2008), as opposed to warmer zones, i.e., arid and tropical climates, where only cooling needs must be met (Lok et al. 2008). Simultaneously, in moderate climate zones, design decisions regarding the building's façade exert the most substantial impact on its energy balance (Raji et al. 2017). Research on energy consumption in buildings shows that the dependence on climatic factors increases with a building's height. The results suggest that these factors provide the main reason for the increase in energy consumption of buildings (Godoy-Shimizu et al. 2018).

In a cool, moderate climate, it is recommended to use windows with a high degree of solar energy transmittance (Ürge-Vorsatz et al. nd). In warm, moderate climates, passive solar systems with increased control of solar radiation access and a thoughtful design strategy are acceptable (Chwieduk 2011). On the other hand, installing solar protection systems on façades is postulated in all climatic zones (Ürge-Vorsatz et al. nd). The annual insolation for Central European countries is measured at the range of 1000–1200 MJ/m^2 (Photovoltaic 2020), which is over twice lower than the conditions observed in the zones with the highest insolation. However, the value is still sufficient to justify the use of solar installations (Voss et al. 2011).

In the search for façade solutions that meet the requirements concerning the energy efficiency and comfort of office space use, the combination of photovoltaic (PV) technology and switchable glazing seems to be a promising alternative. The combination is seen as beneficial, as it entails cooperation between regulated solar protection and energy efficiency based on the use of solar energy. This solution rests on research and application-related experience of the above technologies when applied separately.

This article provides a comparative analysis of PV-EC (photovoltaic-electrochromic), PV-SPD (photovoltaic-suspended particle devices), and PV-LCD (photovoltaic-liquid crystal devices) technologies. The technologies are compared in terms of their application as façade glazing in office building windows (glazed external partitions) in a moderate climate.

1.1 State of the Art

Research concerning façade glazing solutions has been conducted separately for PV glazing and switchable glazing technologies. PV glazing technology is a well-developed field of research, as evidenced by (Skandalos and Karamanis 2015). The main directions for the development of PV modules as glass elements are oriented towards enhancing their visual and thermal properties (Jarimi et al. 2020; Radwan et al. 2020; Sabry et al. 2013), as well as their multi-functionality (Cuce 2016).

PV solar protection with PV technology is also associated with its role as a solar shading device (Fouad et al. 2019; Marchwiński and Zielonko-Jung 2010; Mesloub et al. 2020). In recent years, particular attention has been paid to the concept of Building Integrated Photovoltaics (BIPV). Heinstein et al. (2013), Shukla et al. (2017), Biyik et al. (2017) are among the authors who present a general review of BIPV.

Research on switchable glass mainly concerns technologies such as electrochromic glass (EC), liquid crystal devices (LCD), suspended particle devices (SPD), and gasochromic glass (GC). These studies primarily relate to optical properties and the functioning of these devices (including variation between phases of passive and activated modes). Researchers have conducted a general overview of smart glasses as Addinkton and Schodek (2006), Baetens et al. (2010), Platzer (2003 I, II), Ritter (2007); they referred to both prototypes and commercialized solutions. From an architectural point of view, the author provided a comparative analysis of switchable glasses in terms of their role as a solar protection element (2014), while Mahdavinejad (2011) conducted such an analysis concerning the tropical climate. The use of switchable glass in office buildings provides a frequent research topic, e.g., Dussault and Gosselin (2017), Platzer (2003 I, II), Wilson (nd). Research, mainly on PV, EC, and GC glass, has been conducted at the Fraunhofer Institute in Freiburg (Germany). This research covers both the technological aspects and the issues related to the thermal and visual environment design of interiors, including office interiors (Wilson nd; FIoSE 1999–2019). The rationality of applying EC glass in office buildings was demonstrated in studies conducted by Sbar et al. (2012) who pointed to functional problems of the solution (e.g., the scope and period of the phase transition). Similar studies were conducted for SPD—(Ghosh et al. 2016 I, 2017) and LCD-glass (Macrelli 1995; Jung 2017).

1.2 Aim and Novelty of the Study

Among the numerous concepts of smart windows based either separately on the technologies mentioned above or on the combination thereof, it seems reasonable to examine which of the proposed solutions are appropriate to meet the requirements of the office working environment. On the basis of available technological test results, this article aims to estimate which PV-powered switchable glazing technologies are currently most suitable for façade glazing of office spaces for a moderate climate.

According to the author's assumptions, this article serves as a bridge between technological achievements in the discussed field and office space design requirements. The possibilities of combining switchable glass and PV glass within façade glazing have been recognized in design practice for about 20 years (Lampert 2003). However, none of the scientific papers has provided a collective outlook on linking technological achievements with building design requirements so far. The study closest to the subject matter undertaken in this article has been conducted by Ghosh and Norton (2018). They provided a comprehensive overview of recent developments in energy-efficient and smart windows, including various combinations of PV and switchable glazing technologies. However, PV-powered technologies are only a part of this extensive review, whereas the study does not refer to office windows in a moderate climate.

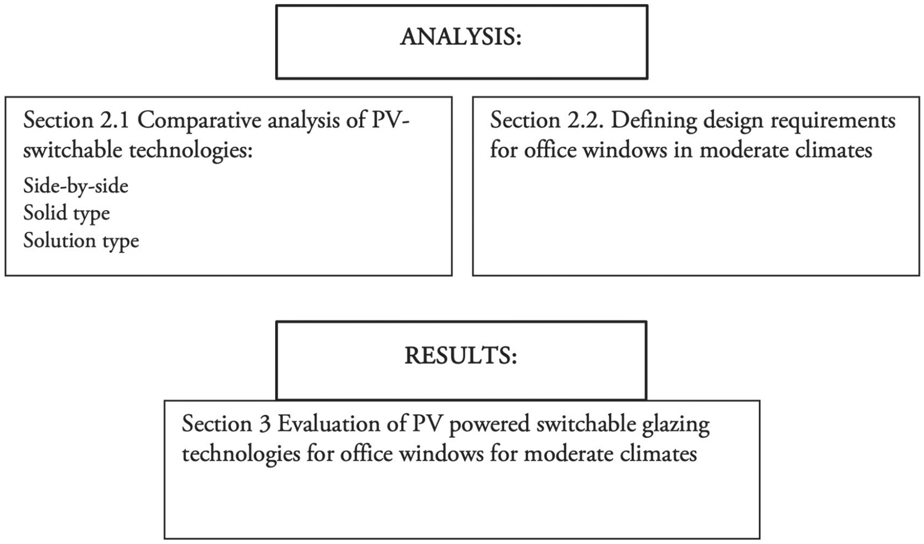
It should be emphasized that this article does not aspire to the title of a scientific study in specialized technological research that involves numerical studies. Its method (section 2) is based on applying the results of numerical studies to estimate the suitability of the discussed technologies for office space design.

2. METHODOLOGY

A comparative analysis of PV-switchable technology was applied to achieve the research goal. The construction-utility features of the currently most advanced solutions, i.e., combinations of PV-SPD, PV-LCD, and PV-EC technologies, were analyzed. Based on the scientific research available, these technologies have been divided into three main groups of solutions, in which the described integration is currently observed:

- Side-by-side technologies,
- Solid type technology,
- Solution-type technology.

FIGURE 1. The diagram explains the structure of this article (by the author).



The thermal, optical-visual, energetic, operation, and use-related features were defined as the most crucial construction and utility issues, based on which the analysis was conducted (section 2.1.)

The subsequent independent step discusses design requirements for façade glazing of the office space in a moderate climate (section 2.2.).

The results obtained in the comparative analysis were confronted with the pre-defined design requirements. This led to evaluating the discussed technologies in terms of suitability of their use in office windows in moderate climates (section 3).

2.1 Comparative analysis of PV-switchable technologies

2.1.1 Side-by side technologies

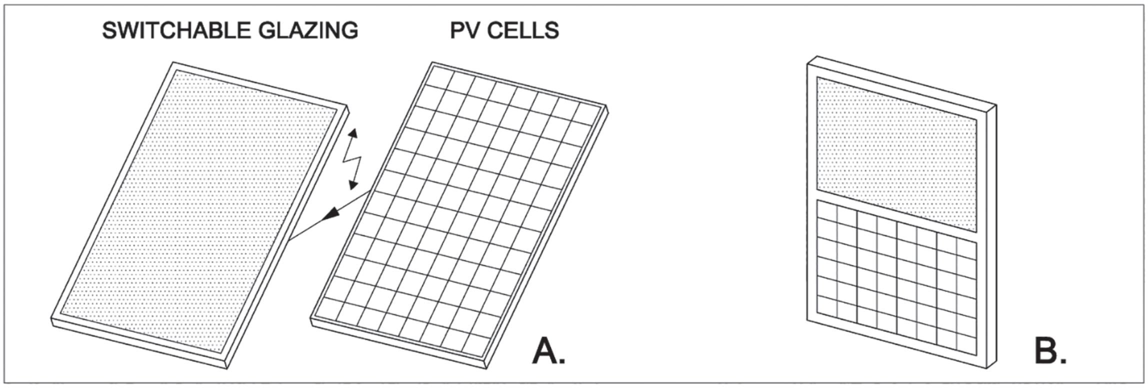
Side-by-side technologies may be defined as a solution that applies the switchable glazing and PV technologies as two separate components, interconnected to form a façade system (Figure 2). Theoretically, no limits exist to the combination of individual PV and switchable glazing technologies. For this reason, these technologies have been discussed separately in terms of their use as façade glazing, based on common criteria such as thermal environments, visual environment, energy performance, and usage.

2.1.1.1 PV glazing technologies:

PV glass is currently based on three technological generations of PV cells.

PV glass, used as façade elements that ensure proper lighting (e.g., windows) made of 1st generation cells, i.e., crystalline silicon, is available in the form of laminated glazing. In this type of glazing, opaque mono- or polycrystalline cells are arranged at certain distances from each other, by means of which they create gaps and, as a result, the effect of partial light transmission (Figure 3a).

FIGURE 2. Side-by-side technology. A-main system components, B-exemplary combination as the solar window (by the author).



PV glazing, in which the 2nd and 3rd generation cells are used (Figure 3 b, c) is of a more uniform appearance, creating a semi-transparent surface. In the case of thin-film cells, the transparency effect is achieved by laser perforation thereof. The following cells are used: thin-film cells—mainly amorphous silicon, cells with CdTe (Cadmium-Telluride), and CIGS (Copper Indium Gallium Selenide). Among the 3rd generation cells, DSSC (dye-sensitized solar cells) and organic cells are applied, which are even more visually homogeneous. On the other hand, though dynamically developing, the technology of perovskite cells remains in the laboratory research phase (Park 2015; Spooner 2020).

THERMAL FEATURES

Emission of heat from the PV cells surface is a side effect of photovoltaic conversion, as the cells absorb the entire beam of solar radiation, including thermal radiation. As a façade element, PV glass is not sufficient in terms of thermal insulation. It has to be combined into a construction system to reduce the value of the thermal transmittance coefficient U. Examples of such combinations include double glazed systems (Muszyńska-Łanowy 2010 I), multi-layer systems (Tina et al. 2013), and other highly insulating technologies, including vacuum glazing (Cuce et al. 2015; Cuce 2016; Ghosh et al. 2018; Radwan et al. 2020).

OPTICAL-VISUAL FEATURES

The transparency of PV glass with spaced mono- and polycrystalline silicon cells depends on the degree of spacing. As the spacing increases, the transparency grows, but the peak power of the PV module decreases. In the case of thin-film technology, the degree of perforation is decisive.

Photovoltaic glass available commercially is characterized by max. 50% transparency, but it usually amounts to 5–30% (Muszyńska-Łanowy 2010 II).

Eye contact with the surroundings, even if more limited than in traditional glazing (change of color and sharpness of the image), is made possible with the application of the 2nd and 3rd generation cells.

Semi-transparent silicon crystalline cells with spaced PV cells cause strong light-shade contrasts in the interior and are characterized by local transmittance of direct solar radiation. The 2nd and 3rd generation cells provide diffused light, comparable to traditional solar control glazing (Marchwiński 2015).

ENERGY FEATURES

Generally, the 1st generation cells continue to be the most efficient ones, and their efficiency amounts to about 25% (Blakers et al., 2013). However, as in all silicon-based cells (including amorphous ones), their effectiveness is sensitive to temperature increase (Addinkton and Schodek 2006), i.e., their efficiency drops by approx. $0.4/\Delta T = 1°C$ (Sarniak 2008).

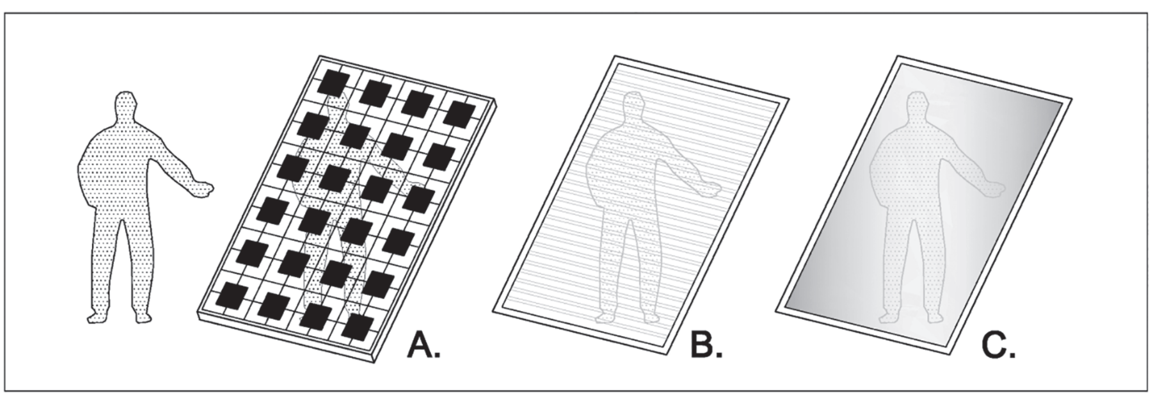
The efficiency of thin-film cells, despite a dramatic increase within recent years, (e.g., the highest reported cell efficiency for CdTe is 22.1% (Wang et al. 2018)), is in practice reported in a range of only 4.1%–12% (Sun et al. 2018).

In the case of 3rd generation cells, perovskite cells are characterized by the highest efficiency. In this case, an immense advancement has been made recently. Nowadays, such cells are similar to crystalline ones in terms of efficiency. These results, however, only refer to the laboratory testing phase and cannot be treated as fully reliable (Mullasery 2016; Park 2015). Organic cells are characterized by a lower efficiency of approximately 8% (Konarka's latest OPV solar cells have demonstrated a record-breaking 8.3% efficiency) (Prasad et al. 2013), whereas DSSC reaches the efficiency of only 3%–7.6% (Park 2015). However, compared to Si-based solar cells, DSSC is low cost and easier to produce. Their performance increases with temperature; thus, they are marked with a bifacial configuration. Their advantage lies in their ability to provide diffuse light (Jasim 2011).

FUNCTIONING AND OPERATION

All PV cell technologies convert solar energy into direct current (DC). They require inverters that turn the energy into alternating current (AC) to use the obtained electricity for utility purposes. The practical service life of silicon cells is estimated at 25 years. The degradation of the 1st and 2nd generation cells progresses in the range of 0.5–1%/year, with thin-film cells being closer to 1% (Jordan and Kurtz 2012). Organic cells demonstrate the shortest lifetime, of about several years, although an increase to 10 years is expected (Zhang et al. 2018). Rapid degradation over time due to the lack of resistance to external conditions (moisture) poses the main problem and also applies to perovskite cells (Mullasery 2016). Currently, no comparable data on the viability of this technology is available. Among the 3rd generation cells, DSSCs demonstrate the most favorable features in this respect (Jordan and Kurtz 2012). However, the most important issue in studying these cells should be to improve their environmental stability, which would lead to longer service life (Andualem, Demiss 2018).

FIGURE 3. PV glazing technologies: examples of semi-transparent PV modules made of A–1st generation PV cells, B–2nd generation PV cells, C–3rd generation PV cells (by the author).



2.1.1.2 Switchable glazing technologies: EC, SPD, and LCD:

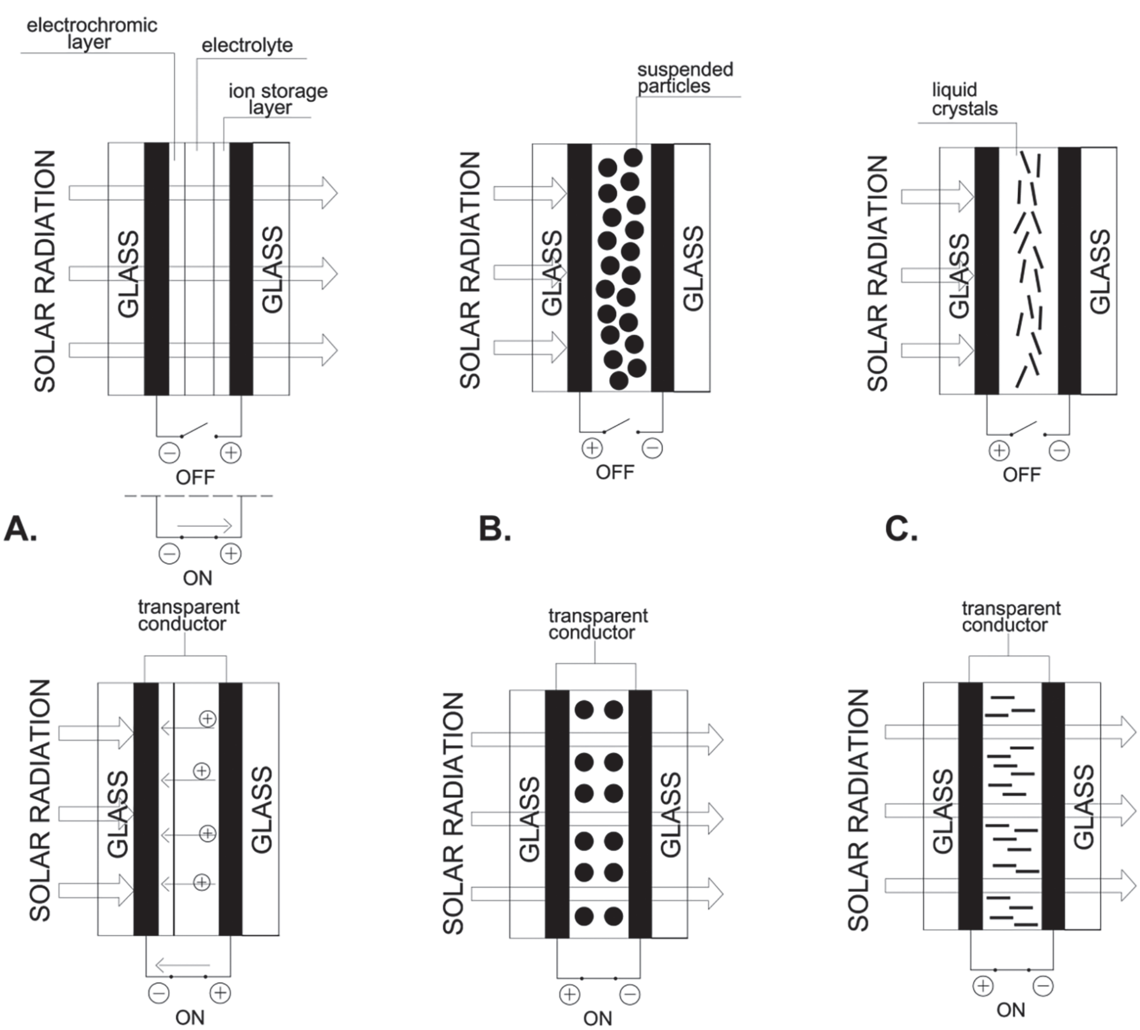
Switchable glazing can adaptively control solar energy gain by changing from "opaque" to "transparent" or from "transparent" to "opaque" given external stimuli such as light, heat, or electricity (Ghosh et al. 2016 II).

EC, SPD, and LCD glazing are the main components of electrically actuated switchable windows.

EC material includes an electrochromic cell which changes from the transparent to the opaque mode employing a redox reaction if a voltage is applied (Ghosh et al. 2013). This technology can be divided into solid and liquid types (Lee-May et al. 2012 I). In the off mode, the EC glazing remains transparent (Figure 4a).

In SPD glazing, a cross-linked polymer matrix with droplets of polyhalide particles is suspended in a liquid suspension located between two glass panes. The particles rotate freely if no electric power is applied (translucent or opaque mode), but become aligned in the presence

FIGURE 4. Switchable glazing technologies: A–EC glass, B–SPD glass, C–LCD glass (Marchwiński 2014).



of an electric supply (transparent mode) (Ghosh et al., 2016 II). In off mode, such glazing remains tinted (Figure 4b).

In LCD technology, a film of liquid crystals is introduced between two layers of glazing. When no voltage is applied, the liquid crystal molecule chains are randomly scattered, and the glazing becomes translucent opal-white. The molecules align when voltage is applied, and the glass becomes transparent (Figure 4c) (Marchwiński 2014).

THERMAL FEATURES

Unlike LCD glazing, SPD and EC clearly impact total solar energy transmission reduction if in the activated mode. LCD windows cannot control heat flow through the glazing (Marchwiński 2014).

For both SPD and EC technologies, switching between the on and off modes occurs through absorption. Thus, opaque EC glazing may provide a heat source inside the building (Ghosh and Norton 2019).

In order to avoid intolerable overheating, an EC layer should be coupled with thermal insulating glazing, including vacuum glazing technology (Ghosh et al. 2013).

The same applies to SPD glazing. Cell characterization obtained by outdoor tests of SPD glazing suggests that this solution can, and should be, incorporated with double or vacuum glazing in a low heat loss window with variable solar heat gain (Ghosh and Norton 2019).

EC glazing in a tinted mode is characterized by a relatively low g-value (0.05–0.30). SPD glazing has a higher g value (~0.4–0.7 opaque-clear state). Moreover, EC glazing is distinguished by a higher g-value (Figure 5) (Marchwiński 2014).

Contrary to EC, SPD glazing coupled with PV does not use an electric current to control excess solar heat gain. The unused PV output can be stored in a battery for later use. On the other hand, the SPD needs to be in transparent mode to allow solar gain and daylight to enter the room (Ghosh et al. 2016 II).

OPTICAL-VISUAL FEATURES

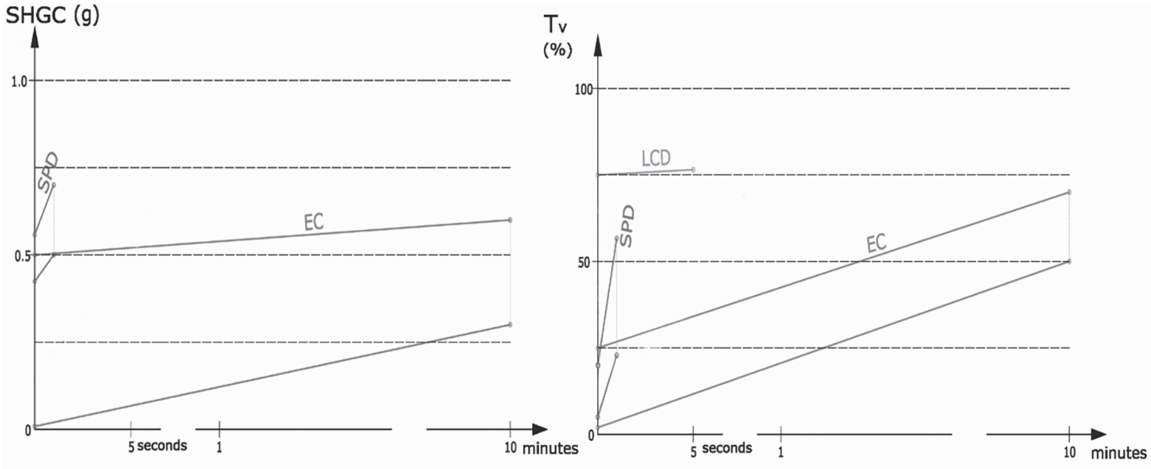
EC and SPD glazing noticeably change their transparency (T_v factor values) according to their mode. As already mentioned, LCD glazing does not affect the way solar radiation is transferred, and its influence concerning lighting conditions is negligible (Figure 5). Noticeable differences in terms of visual contact behavior are seen among all three technologies (Figure 6). In the case of EC, the effect is that the glazing switches between a clear and transparent or semi-transparent tinted mode with no degradation of view. In this case, glazing can be modulated to any intermediate mode between clear and fully tinted but provides visual contact across their switching range (Marchwiński 2014).

SPD windows provide an obstructed view when dimmed. They can also be opaque, in which case they function as a "view shield." This feature is also typical of LCD glazing, which usually comes in two modes only: the clear mode and diffusing mode. SPD and EC glazing may reach intermediate modes (Marchwiński 2014).

All these technologies provide visual contact in their clear mode. Nevertheless, a slight haze or scattering may be observed. Furthermore, EC windows are slightly yellowish when in the off mode (Marchwiński 2007).

Unlike in EC, SPD coupled with PV requires no voltage to protect interiors against excessive solar light (dimmed mode), but it does require electric current from PV cells to remain clear. Research shows that such a combination offers a transparency range between 5 and 55% using 1.19 W/m^2 to maintain its transparent mode (Ghosh et al. 2016 II).

FIGURE 5. Physical behavior of EC, SPD, and LCD glazing technologies (activation range and switching time) in terms of their total solar energy transmission (left) and light transmission properties (right) (Marchwiński 2014).



ENERGY FEATURES

Since the transparent mode is obtained in LCD and SPD technologies when the electric current is continuously applied, such solutions can be considered more energy-consuming than EC windows. SPD typically requires 50–100 V AC to be activated from the tinted (off) mode to the near-transparent (on) mode. Depending on the amount of voltage, the glazing can be modulated to any intermediate mode of opacity. Power requirements equal ~5 W/m^2 for both switching and maintaining a constant transparency mode. The value, however, is expected to decrease to 1W/m^2 (Lee-May et al. 2012 I). For 1 m^2 of area, SPD glazing only uses 10.42 kWh of power per 24 h/365 days (Ghosh and Norton 2018).

The same amount of power (~5 W/m^2) is required for LCD glazing to remain in the transparent mode. The glazing operates at a power consumption of between 24–100 V AC (Deb et al. 2001). Devices remain transparent only for as long as the electric field is maintained (Compagno 1999).

A relatively low T_v (visible transparency) factor of SPD glazing means a reduced amount of natural light and thus increased use of energy consumed by artificial illumination (Marchwiński 2014).

EC glazing causes a reduction in transmitted radiation while transparent. Such devices need less energy to function and let more natural light inside than the SPD do in their bleached mode. An EC device requires low-voltage power of up to 10 V DC to change its mode, whereas the tint conversion process requires less power at higher environment temperatures (Carmody et al. 2004).

The device is switched to its desired mode for some EC types (polymer laminate), and no power is needed to maintain it. This type of device is characterized by long memory once switched (power is not required for three to five days to maintain a given switched mode) (Deb et al. 2001).

Compared to traditional anti-solar (reflective) glazing, EC technology application can reduce the building's energy use by 25% of heating and cooling needs, 50% of lighting, and 30% of peak power demand (Deb 2000).

FUNCTIONING AND OPERATION

Significant differences between the abovementioned technologies may be observed concerning their behavior in terms of switching time. The transition of SPD glazing happens immediately (within less than a second), LCD glass changes its mode within several seconds. In EC technology, full coloration is typically achieved within several minutes (Figure 5) (Marchwiński 2014).

PV powers the EC glazing directly, as both technologies operate on direct current. The current generated by PV in insolation conditions coincides with the need to tint the glazing in order for it to function as a protection element against excessive solar radiation. Therefore, the conversion process requiring voltage and the process of generating electricity by PV coincide in time (Lee-May et al. 2012 I; Ghosh and Norton 2019). SPD and LCD are electrically actuated forms of glazing whose transparency is changed when an alternating current is applied. For the same reason, these technologies require the use of an inverter. The presence of an inverter between PV and SPD glazing makes the process complicated. It may result in significant power losses (Ghosh et al. 2016 II).

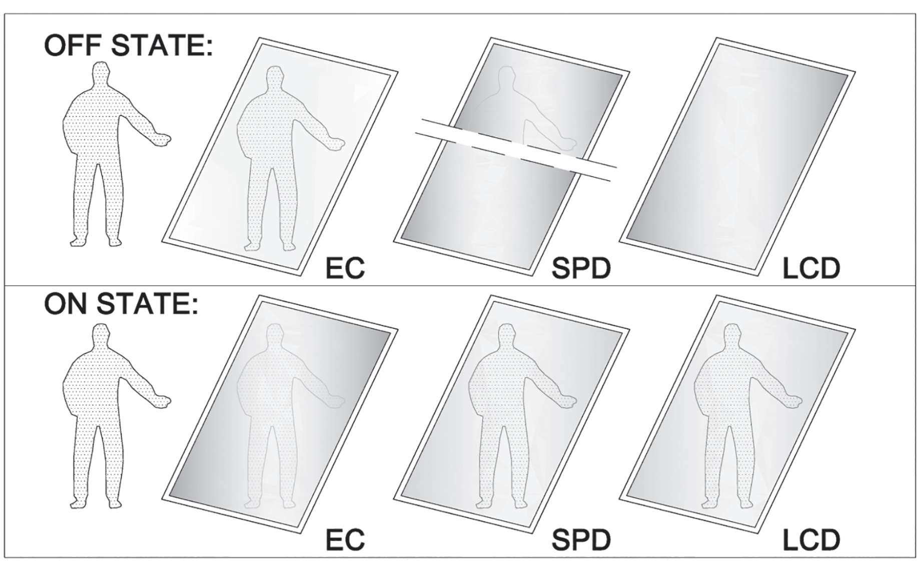
Moreover, low solar radiation on days with overcast and intermittent sunlight may not generate sufficient power to supply the SPD glazing continuously. Thus, battery storage is recommended for PV-powered SPD glazing (Ghosh et al. 2016 II). A battery storage module is another essential device to accompany the PV-SPD combination (Ghosh and Norton 2019). Analogically, LCD glazing should be equipped with inverters and batteries, although this combination is less recognized (Ghosh and Norton 2018).

2.1.2 Solid type technology: monolithic tandem and photoelectrochromic (PEC) technology

Solid type technology combines solid elements of both technologies (PV and switchable glazing) within a uniform product in the form of the so-called self-powered smart glass.

The glazing structure is rather complicated, as it comprises layers responsible for the switching process and the photovoltaic conversion. The latter layer is used to generate an electric

FIGURE 6. Optical properties and behavior of EC, SPD, and LCD glazing technologies in "off" and "on" states (by the author).



current that drives the conversion of optical parameters of the glazing. This technology currently applies to PV-EC (Ghosh and Norton 2018).

Thin-film PV cells, esp. A-Si and DSSC, perovskite, and organic PV can be integrated with solid type EC materials (Ghosh and Norton 2018; Lee-May et al. 2012 I).

Until recently, two types of solar-powered EC devices have been available. The first one is a tandem structure silicon (Si) based PV–EC device (Benson and Branz 1995, Bullock et al. 1996, Gao et al. 1999, 2000), whereas the latter is a DSSC based photoelectrochromic (PEC) device (Ahn et al. 2007; Hauch et al. 2001; Leftheriotis et al. 2010).

The monolithic, tandem PV-EC technology consists of stacked layers of the photo absorbers and EC active materials in a single device (Lee-May et al. 2012 I). The solution (Figure 7a) requires a transparent PV coating that drives the EC device. A 25 mC/cm^2 charge is needed for the EC device currently employed to complete the tinting or bleaching process (Deb 2000). Coupling PV and EC together is not an established design and manufacturing practice (Ghosh et al. 2016 II).

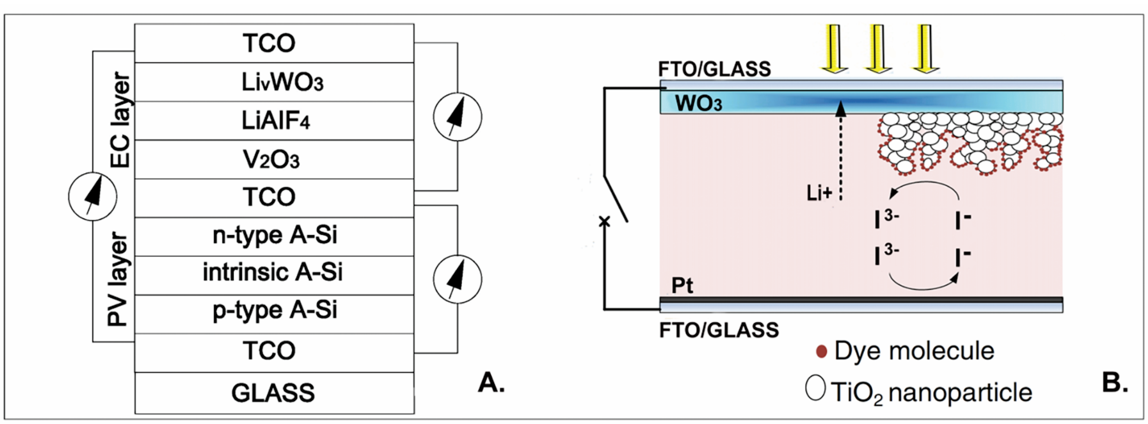
PEC technology is one that is currently sparking the greatest interest (Lee-May et al. 2012 II). It may be described as an EC device installed between DSSC devices (Lee-May et al. 2012 I, II]. PEC are photoelectrochemical cells. They consist of DSSC, usually based on mesoporous TiO_2 that traps solar energy in order to provide the electric charge required for reversible conversion of optical properties of an EC film, typically made of WO_3 (Figure 7b). Both DSSC and EC elements are incorporated into the same device (Leftheriotis et al. 2013).

THERMAL PROPERTIES

The EC layer prevents solar heat by absorption rather than reflection, and it may become quite hot when irradiated (Lee-May2002). PV cells operate in a similar manner. Therefore, it can be assumed that the effect of heat absorption in the cases of EC glazing and the PV cells overlap, which creates the risk of undesirable heat emission to the interior.

It is required to use PV-EC glazing in a two-pane or multi-pane set with an insulating layer, including vacuum glazing. However, increasing the temperature on the EC surface accelerates the ion flow reaction, which results in a faster phase transition and less demand for electricity. This fact promotes thinning of the PV layer, which positively affects the transparency of the entire tandem set (Deb 2000).

FIGURE 7. PV-EC solid types technologies: A–monolithic tandem structure Si-based PV-EC (Deb et al. 2001) B–PEC technology (Leftheriotis et al. 2013).



OPTICAL-VISUAL FEATURES

- Light transmittance/transparency: the problem lies in assuring the proper transparency. The PV and EC layers may cause difficulties in achieving the accurate level of the T_v factor. Therefore, PV cells must be thinner and as transparent as possible. The main technical challenge lies in reducing the device's thickness to less than 100 nm for semi-transparency. When the semi-transparent PV thin films become very thin, electrical short circuit occurs easily and renders the PV-EC stacks useless. This problem has made the manufacturing of monolithic PV-EC devices very challenging (Deb 2000). The occurrence of potential electrical short-circuits requires an insulating layer between the PV and EC connectors. However, the insulation layer requires metal bus bars and fingers (Figure 8). The introduction of such elements negatively affects the aesthetics and transparency of the entire set, although it generally remains acceptable in aesthetic terms (Deb et al. 2001).
- Optical contrast: the critical issue in silicon-based PV-EC device development lies in its low optical contrast between opaque and transparent modes (Figure 9a) (Lee-May et al. 2012 I). In semi-transparent perovskite photovoltaic and solid-state electrochromic cells, low transparency, which amounts to a range between 8.4% and 26% of average visible transmittance (Cannavale et al. 2015), is a problem.
- Phase transition: the phase change is not a uniform one (Ghosh et al. 2016 II). This fact applies to larger surfaces, i.e., it is adequate in the case of windows (e.g., 1 m^2). In such situations, resistive losses occur within the EC (on transparent electrodes), reducing charging with current from the PV. The tinting and bleaching processes of the window become slow and non-uniform (Deb et al. 2001).
- Color: a common problem, also observable in EC glasses (without PV), is the yellowish shade of the PV-EC glazing in the bleached mode. This tint change slightly distorts the color of the surrounding elements. In the dimming mode—by default, their shade is deep blue (Marchwiński 2007).

FIGURE 8. The schematic of a large-area monolithic PV-EC device structure (Deb et al. 2001).

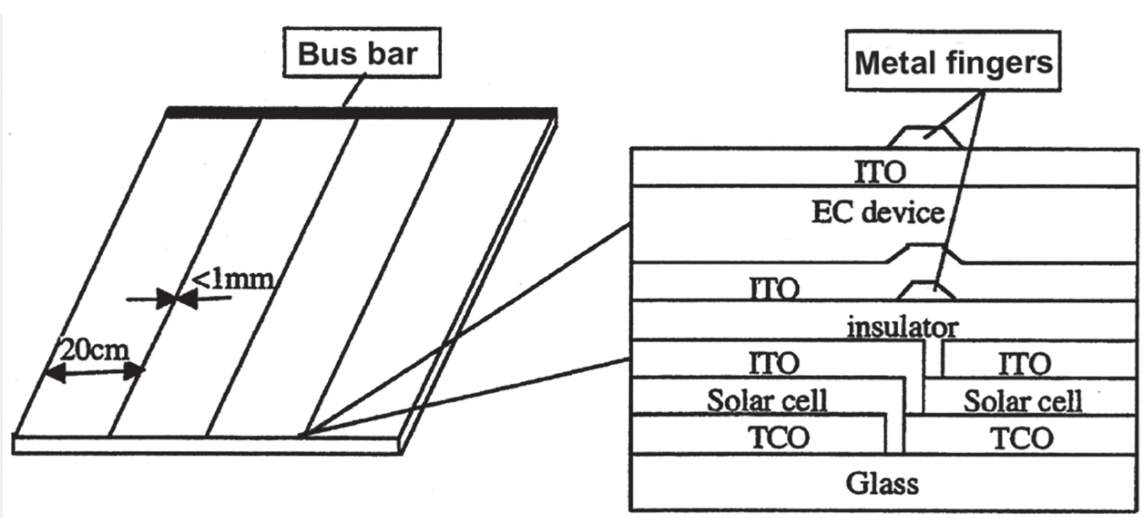
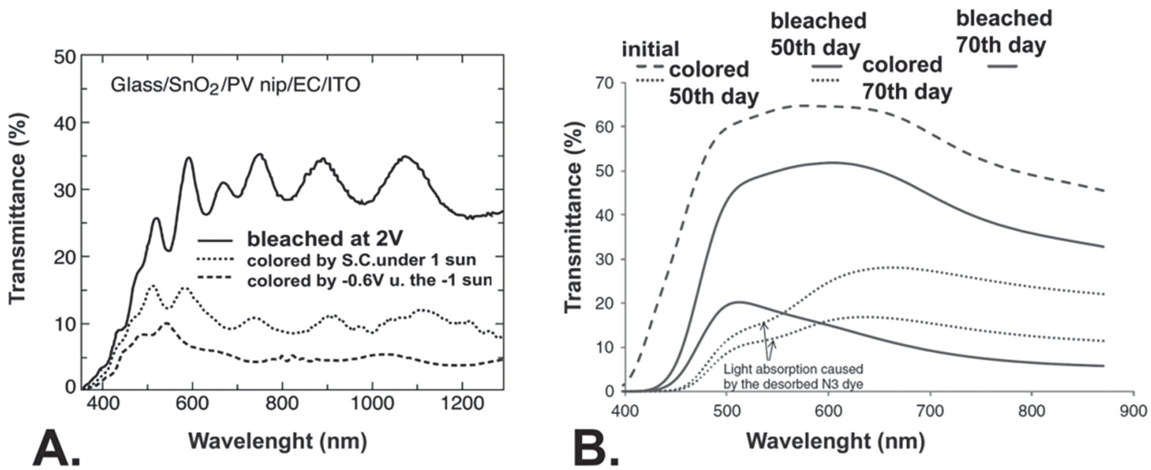


FIGURE 9. Transmittance spectra of: A–monolithic tandem structure Si-based PV-EC device (Deb et al. 2001) B–PEC device (Leftheriotis et al. 2013).



ENERGY-RELATED FEATURES

Monolithic tandem and PEC technologies operate as passive devices, with no demand for external power for operation. They can act both as an individual electricity generator as well as semi-transparent solar window, which affects a decrease in energy consumed by air conditioning systems (Leftheriotis et al., 2013).

PV-EC technology integrated with building applications offers enormous energy savings. As reported by NREL (Deb et al. 2001), 1 kW_p of PV power can remove approximately 3 W_p of heat from the building envelope, while the same 1 kW_p of PV used to activate a PV-EC window can avert 110 kW_p (Deb 2000; Lee-May et al. 2012 II). The technology requires only about 0.1 mA/cm^2 current density supplied from the PV device to tint the window within 5 minutes (Deb 2000).

FUNCTIONING AND OPERATION

- Switching time: In PV-EC monolithic technology, the time required for phase transition increases with the glazing surface. It ranges from a few seconds to several minutes (Ghosh and Norton 2018), but in the case of windows, it is counted in minutes, as in EC glazing without PV.
  In the case of PEC technology, the speed at which tinting and bleaching occur does not depend on the surface of the device, but only on the internal electrical field generated by the photovoltaic unit. Thus, the time needed for tinting, measured on small laboratory samples, is also applicable to large surface windows (Leftheriotis et al., 2013).
- Lifespan: the main disadvantage of DSSC-PV lies in its low stability due to photochemical degradation of sealing, solvents, and dyes (it is an issue related to dyed cells) (Macht et al. 2002; Nogueira et al. 2006). Monolithic tandem PV-EC seems to be advantageous in this field, but its lifespan is also limited. Generally, EC materials can only be used for nearly 2000 cycles (transparent to opaque; opaque to transparent) (Ghosh and Norton 2018). Moreover, as the semi-transparent PV thin films become thinner, the electrical short circuit effect occurs more readily. In such cases, the PV-EC set is rendered inoperable (Ghosh et al. 2016 II).

- Performance: the PV and EC technologies work on direct current. This makes the PV-EC structure simpler as inverters are not required. As the operation thereof complies with solar radiation, no batteries are needed either. Nevertheless, PV-EC tandem structure, in case of which a short circuit current between deposited layers is observed, proved difficult to produce in the form of large surface devices. The device must be well-designed to implement a monolithic PV-EC structure. Each of the nine layers of the tandem device must be optimized to obtain acceptable device performance (Deb et al. 2001), as shown in fig. 7a. Despite their disadvantages related to low stability (Figure 9b), PEC glazing is of simpler construction and, thus, may seem more reliable in terms of use. For this reason, it is considered to be a potentially low-cost device. It is also well-matched to typical diffuse solar spectra (Mehmood et al., 2017).

2.1.3 Liquid (solution) technology

This technology assumes combining thin-film silicon cells with liquid EC material. This innovative solution-type PV-EC device applies an EC solution disposed between a transparent non-conductive substrate and a semi-transparent silicon thin-film solar cell (Si-TFSC) substrate (Figure 10a). Moreover, other PV materials, such as CIGS and CdTe, can also be integrated into the PV-EC device (Lee-May et al., 2012 II).

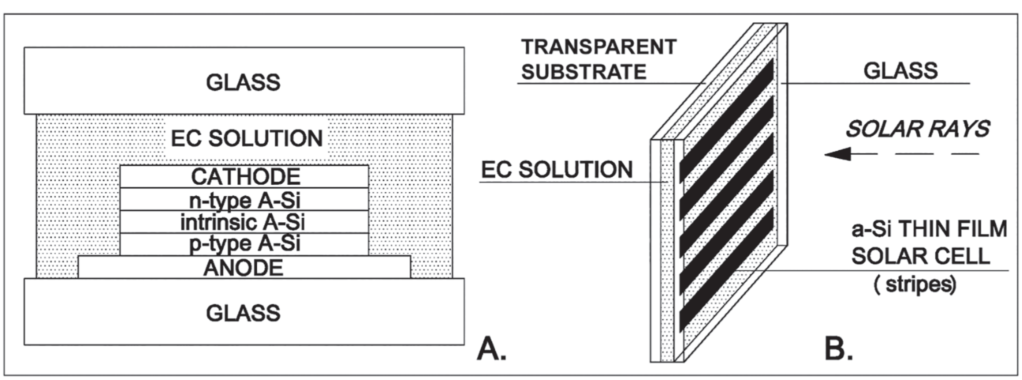
THERMAL FEATURES

As the solution-based technology is new, little research on the thermal operation of this type of PV coupled glazing is available. It may be assumed that its functioning is similar to that of the solid type PV-EC. Both technologies are analogical in that their structure consists of PV and EC materials absorbing heat. The differences may arise from the consequences of solid and liquid modes of EC material and various thicknesses of the glazing compounds. Regarding the influence of the thermal environment resulting from solar radiation, potential differences may be noticed in solar spectra transmittance operation. A higher degree of optical contrast (see below) may affect better solar protection.

OPTIC-VISUAL FEATURES

- Light transmittance/transparency: light transmittance of solution-type technology is enhanced compared to solid tandem PV-EC glazing. The increase in transmittance

FIGURE 10. PV-EC liquid (solution) type technology: A–section B–elevation (Lee-May et al. 2012 II).



is due to the thinner Si-intrinsic layer. It is possible because the PV-EC device can be driven with low voltage and a low amount of current, whereas the demand for photo potential and photocurrent produced by the Si-TFSC is reduced (Lee-May et al. 2012 I, II).

Visually, the solution type PV-EC glazing is distinguished by the stripes on its surface—thus, it is not visually homogeneous (Figure 10b).

- Optical contrast: the overall transparency and the color contrast of the solution-type PV-EC device are enhanced. Based on the research sample of several centimeters, the transmittance change between the tinted and bleached modes amounts to 70% (Figure 11a) (Lee-May et al. 2012 II).

ENERGY-RELATED FEATURES

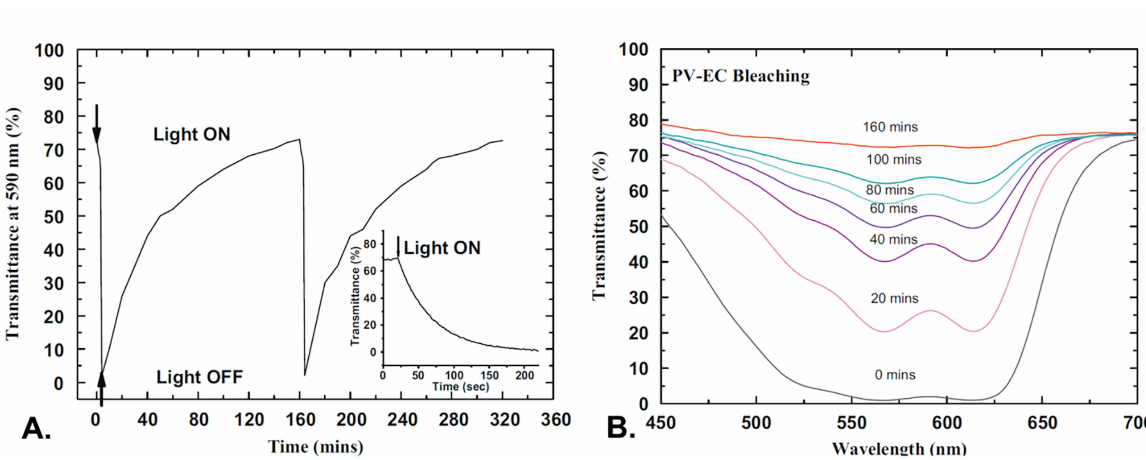
Due to the self-bleaching property of the EC solution, the solution-type PV-EC device restores its transparency when the sunlight declines. No voltage is needed to change the mode from tinted to bleached one. The electrical power generated by the PV-EC module can be controlled by an additional output switch layout coupled with the Si solar cells. Given photoelectric conversion and optical modulation properties, the PV-EC solution device, similarly to the solid-type device, can function as a solar cell module and as self-powered smart glass (Lee-May et al. 2012 II). Further investigation is required to compare solid and liquid PV-EC technologies in terms of energy efficiency.

FUNCTIONING AND OPERATION

- Switching time: the tinting time is 200 sec. (Figure 11a), and the self-bleaching duration requires about 100 min. to recover 85% of its original transmittance (Figure 11b) (Lee-May et al. 2012 II). These amounts are regarded as too long for practical applications (Lee-May et al. 2012 I).

  An on/off switching control for this solution-type PV-EC device is currently under development.
- Life-span and performance: the solution-type PV–EC may cause erosion in Si layers (Hu et al. 2012). However, planar PV-EC design, with different anode and cathode blocks, can solve short-circuit-related problems encountered in the monolithic PV-EC

FIGURE 11. Transmittance properties of liquid type PV-EC device (Lee-May et al. 2012 II).



(Deb et al. 2001; Gao et al. 1999). Moreover, the planar distribution of electrodes in the entire semi-transparent Si solar cell substrate creates a uniform electric field, making large area PV-EC module application feasible (Lee-May et al. 2012 II).

2.1.4 Summary

The conducted analysis allows us to distinguish the following configurations between PV technologies and switchable glazing, as described in Figure 12.

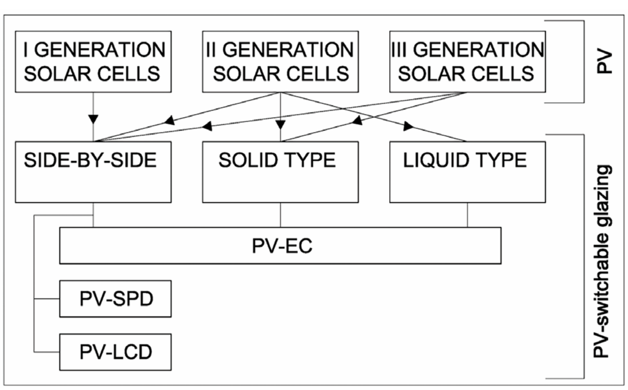
2.2 Defining design requirements for office windows in the moderate climates

Along with the fundamental importance of humanization aspects of the office environment, it has become popular to emphasize the ecological elements of office buildings. These mainly relate to emphasizing the connection with the natural environment and introducing natural lighting, climate, and greenery to the interior (Marchwiński 2005; Złowodzki 1997). Natural light is the most beneficial to humans, yet it accounts for approximately only 25% of the total lighting in offices. It may increase with such modifications as the proper orientation of the building towards the directions of the world (it is estimated that only 24% of artificial light is necessary) (Złowodzki 1997). Along with the humanization of the workplace, requirements increase for energy efficiency and operational reliability of systems responsible for the conditions within the working environment. In designing office windows, a balance (optimization) between energy efficiency, daylighting, and visual comfort is sought (Pilechiha et al. 2020).

In line with the abovementioned trend, the following design postulates can be identified regarding the role of windows in office workplaces:

- Office workstations should be located close to the window to provide maximum natural light and a view outside. Natural light and a view outside are desirable for psychological reasons (Tymkiewicz 2012).
  By employees, daylight is seen as pleasant, and it brings about 40% savings compared to objects illuminated with artificial light only (Złowodzki 1997).
- In the thermal aspect, windows must protect rooms against both overheating and heat loss. For this purpose, technological solutions with a reduced U coefficient (e.g., insulated glass) are required. The temperature on the surface of window panes should not differ from the temperature of the air inside by more than 4° C (Złowodzki 1997).

FIGURE 12. Configurations between PV and switchable glazing technologies (by the author).



In a temperate climate, double-glazed façades create a thermal buffer zone and are thus considered particularly advantageous (Stec 2006). In single-glazed external walls, façades with windows allow for easier maintenance of stable thermal conditions than façades covered fully with glass (Daniels 1997). Windows require sun protection during summer and transitional periods. The distribution of solar radiation incident at an angle of 50° through a single pane is as follows: transmission: 80%, absorption, and reflection: 10% each (Złowodzki 1997). Hence, it is essential to strive to control solar radiation transmittance to the office interior.

- In terms of lighting aspect, the windows cannot cause glare, too high contrasts, excessive or insufficient light intensity, or asymmetry. Windows, especially eastern and western ones, require protection in the form of external or internal shading elements. The following conditions are decisive for proper, sharp, and minimizing vision in terms of visual fatigue: illuminance, glare reduction, uniform brightness (brightness, luminance) of the surface, and brightness uniformity over time (Gradjaen 1973).
- Regulation possibility, e.g., for controlled ventilation and the control of the natural light flow, is believed to reduce employee-induced stress (Tymkiewicz 2012; van Esch et al. 2019). The windows, if possible, should be fully or partially openable, and employees should be able to individually adjust the parameters of the thermal and lighting environment to their needs (Marchwiński 2005; Scheuring and Weller 2020)
- Maintaining the complete transparency of windows is recommended, i.e., uninterrupted visual contact with the surroundings. Color distortion, opaque elements in the field of view are considered undesirable (Marchwiński 2005; van Esch et al. 2018).
- Passive and active energy gains in high-efficiency solar windows—windows should serve as an element that acquires thermal energy in cold periods, namely as an element of passive solar systems (Marchwiński and Zielonko-Jung 2005). It is also desirable that windows play a year-round role as electricity generators in BIPV systems (Marchwiński 2012). The operation of such windows should not generate energy losses (Marchwiński 2010).
- Reliability, ease of use, easy repair, and maintenance of windows.

In conclusion, considering the above design postulates, the following general requirements for office windows and workplaces in a moderate climate can be formulated:

- access of ambient dispersed natural light,
- stable temperature parameters: protection against heat and cold,
- glare control,
- possibility for window regulation, privacy control, and contact with the surroundings,
- energy efficiency,
- reliability in technical-utility terms.

3. RESULTS—EVALUATION OF PV-POWERED SWITCHABLE GLAZING TECHNOLOGIES FOR OFFICE WINDOWS

3.1 Access of ambient dispersed natural light

LCD glazing is characterized by a relatively high daylight transmittance and can thus provide a high level of natural light. However, the main disadvantage of such glazing is the lack of control over the degree of light access. EC glazing, in the bleached mode, allows more natural light than the SPD glazing. EC glazing is advantageous to light office spaces in moderate climates where daylight is desirable, especially as its transition range is substantially more extensive. However, a slight change in the tint of sunlight passing through EC glazing into the office room may not be tolerable for everyone (Lee and Di Bartolomeo 2000).

Among PV cells, the 2nd and 3rd generation cells prove especially valuable. Contrary to windows with 1st generation cells separated from each other, recent generations of PV cells provide diffused light. Thus, they are capable of evenly illuminating the room with daylight. Due to intense light and shade contrasts, windows with separated 1st generation PV cells should not be recommended for offices, as this feature can make office work uncomfortable. This aspect is critical in windows with an eastern or western exposure, i.e., under conditions of lower (at a lower angle to the horizontal one) incident sunlight.

In side-by-side systems, it should be assumed that windows with switchable glazing rather than PV cells are applied as the primary partition by means of which to illuminate offices.

For solid monolithic PV-EC windows, the lack of full transparency may be seen as one of the significant disadvantages. The windows face similar disadvantages to the ones observed in the case of PV cells in terms of daylight transmittance. Any improvement in daylight transmittance parameter occurs at the expense of the PV cell power or operation (short circuit). Liquid technology offers an advantage in this field. Yet, it currently seems unlikely to compete with an optimally designed side-by-side set, in which the PV and switchable technologies occur separately. The latter system is characterized by higher flexibility within the façade. Another significant problem with solid technology is the low optical contrast between the bleached and tinted mode—in this aspect, liquid technology proves more advantageous.

3.2 Stable temperature parameters: protection against heat and cold

All the discussed switchable and PV technologies absorb solar heat in their structure. Thus, the potential risk of heat being emitted into the interior arises. Consequently, overheating and uneven temperature distribution inside may occur. Neither PV glass nor single switchable glazing is adapted to the heat transfer coefficient U requirements for glazed façade partitions in offices. This problem leads to overheating and heat loss of the office spaces, which is particularly important in moderate climates.

It seems that integrated solutions, especially monolithic tandems, that combine PV and switchable technologies within one structure may be characterized by a greater degree of heat absorption (research in this field is required).

For the above reasons, all PV-switchable technologies must be combined into glazing units for which the required thermal parameters have been determined (discussed in the analysis). It is especially desirable to use these solutions in double-glazed façades with silicon PV cells. The air void functions as a buffer space that channels the heat away from the surface of the cells. This process has a positive effect on the efficiency of glazing.

A relatively low g-value of EC indicates good protection against solar heat. In cold climatic conditions, it is suggested that the EC window should operate in a bleached mode during a heating season (Ghosh et al. 2013; Marchwiński 2014; Marchwiński 2021).

With its higher g value, SPD glazing may be regarded as a less efficient solar protection measure (Addinkton and Schodek 2006; Compagno 1999; Haldiman et al. 2008). Moreover, as a higher g-value range distinguishes EC glazing, it may be better suited to applications in changeable thermal conditions of moderate climates. As it lacks the properties of solar protection glazing, LCD glazing cannot be considered a component used for shaping the thermal environment.

The disadvantage of EC glazing lies in its lengthy phase transition concerning office working places located close to windows, and this aspect renders EC glazing ineffective for such applications. The introduction of additional solar protection elements is required to protect workspaces against overheating (e.g., external blinds). In this field, SPD glazing demonstrates a significant advantage.

In the case of solid-type PV-EC glazing, relatively low outside air temperatures in moderate climates may not be conducive to increasing the swiftness of phase transition. The PV-EC liquid glazing technology is promising, as a greater range of phase transition parameters may be observed, i.e., concerning the lower limit of phase transition parameter. This feature may make PV-EC glazing a better solar protection measure to protect against overheating of office spaces.

3.3 Glare control

The assessment of the glass partitions in terms of glare control results from two features: the degree of minimum sunlight transmittance and, in the case of switchable technology, the switching time. The first feature has partially been discussed in section 3.1. However, according to the discussed aspect, the lowest (rather than the highest) parameters of the T_v coefficient are significant. EC glazing that reaches the lowest T_v value parameter when completely dimmed may seem to be the most effective anti-glare protection. Yet, even if SPD glazing demonstrates a higher T_v value when darkened, it is generally less transparent and may prove more effective for practical use. It may be applied to compromise the need for natural office lighting and protection against the glare effect. While fulfilling both functions, it does not require frequent adjustment. In turn, LCD glazing cannot be seen as a glare control measure at all.

The 2nd and 3rd generation PV cells can also serve as glare control in side-by-side systems. On the other hand, PV windows with 1st generation cells fail to provide adequate protection, and gaps between the cells are generally large enough to allow direct sunlight to pass through. Hence, their location should not be at the level of the user's eyesight or above.

The phase transition time is of particular importance for glare control. In this respect, EC glazing, for both side-by-side and integrated solid systems, particularly liquid EC glazing, displays unsatisfactory features. Solving this problem when it comes to EC technology is critical. The issue is significant in temperate climate conditions, as it is characterized by relatively dynamic conditions of the change in the intensity of solar radiation falling on the glass façade partition. In practice, all PV-EC solutions need to be supported by spatial shading elements (blinds, curtains) to provide adequate protection against glare. SPD glazing is decisively at an advantage in this respect, as its immediate phase transition makes it a practical anti-glare protection element.

In a side-by-side PV-SPD system, where the PV comprises a semi-transparent PV module, the SPD glazing should serve the function of glare protection.

3.4 Window regulation possibility, privacy control, and contact view with the surroundings

Glazing technologies are marked with the ability for their optical features to be adjusted. Therefore, these technologies offer an advantage over non-adjustable glazing, including PV windows.

Liquid crystal windows are best suited for privacy control since they act as a view barrier while in the off-mode. Also, SPD technology is known for providing reasonable privacy control. In this sense, SPD may be perceived as an alternative to LCD. However, their primary advantage over LCD is related to their feature of offering a more oblique view. Change in tint occurs instantly. The user may benefit from this technology, as the voltage it requires can be varied to provide various tint levels. Therefore, transmission properties can be modified in such a way as to suit any particular external environment.

The use of EC technology, in turn, makes it possible to maintain eye contact with the environment even when the device is in the phase of full tint (active state). However, it is not possible to keep a fully unscattered view. Although the EC glazing is transparent in its off mode, some users complain about the annoying yellowish tint—the drawback is acceptable to 2/3 of users (Wilson nd).

To conclude, LCD and SPD are especially appropriate for applications where user privacy is required, whereas visual contact with the surroundings is not a priority. Thus, both technologies are inappropriate when both viewing and solar control (heat and light) are needed simultaneously. The main advantage of EC glazing may be sought in the fact that the technology can exert impact on the light environment, as it regulates solar light transmission levels. At the same time, the technology fulfills the primary role of the window, namely visibility to the outside. This function proves the most relevant for office windows.

In the case of side-by-side systems, PV cells, depending on their transparency, can interchangeably be used as a privacy control device or a window with which to secure contact with the surroundings.

This alternative applies to 2nd and 3rd generation PV cells. However, even the most transparent types of PV cells stand no comparison to traditional windows. Regarding the 1st generation cells, their use may be mainly limited to the role of a privacy control device. PV windows, even with widely spaced PV cells, render visual contact with the environment problematic. Considering the above, switchable glazing, rather than PV windows, should perform the function of windows in office spaces where eye contact is generally desired.

In this aspect, integrated PV-EC solid and liquid technologies face a more significant challenge. As differences in construction arise between these technologies, combining EC and PV solutions results in their visual heterogeneity. The characteristic stripes can be perceived as annoying in eye contact with the surroundings, regardless of how far spaces between them are. In addition, a problem arises related to color distortion of the external image (as with homogeneous EC glasses). To potentially apply such solutions in future office windows, it will be of particular importance to increase the transparency of PV cells. At the same time, technical and operational issues need to be overcome. Due to the use of EC technology, the integrated PV-EC systems, both solid and liquid, are improper to serve the role of a visual barrier.

3.5 Energy efficiency

In moderate climates, the most transparent mode provides a natural condition for office windows. For this reason, EC seems to be most suitable for windows, as with this technology, they remain clear with no need for electricity consumption. LCD and SPD, both of which need electric power to stay in transparent mode, may be perceived as more energy-consuming. On the other hand, in SPD, electric current consumption is minor, so when coupled in a side-by-side system (PV-SPD), the electric consumption of the device may be rendered unnoticeable.

The most significant electric energy surplus may be expected in side-by-side systems when PV modules are made of 1st generation PV cells. This situation happens due to the higher efficiency of such cells. Such an effect may be achieved if the PV cells power the switchable window while being integrated with the electrical grid of the building. When coupled with EC glazing, surplus energy is sure to be relatively higher. Moreover, in that respect, significant advancements may be expected in the case of perovskite PV cells.

In integrated systems, both solid and liquid ones, only less efficient PV cells of the 2nd and 3rd generation can be applied. However, these devices are also likely to generate a surplus of energy current.

However, in terms of energy savings, the most significant advantage of PV cells should be perceived in protecting interiors against overheating. This aspect refers both to side-by-side and integrated solid and liquid systems. In the previous case, both SPD and EC may function as protection measures. EC seems to be slightly more favorable due to its highest switching range with the highest Tv value. These parameters allow for solar control while offering the use of the most significant amount of natural light. Thus, energy savings may be achieved by the reduction of electrical lighting.

LCD windows do not provide energy savings, as they are incapable of controlling transmitted solar radiation, as mentioned in section 3.2.

In the case of solid and liquid PV-EC systems, more research is needed. Yet, as liquid devices are characterized with higher optical contrast, a more substantial influence on the energy savings of the building may be assumed.

3.6 Technical-utility reliability

The switchable glazing technology is characterized by a complex structure that carries the risk of malfunctioning. The complexity degree tends to be higher in the case of integrated technologies, both solid and liquid. Generally, efforts to improve operational parameters result in decreasing electrical performance of the entire system (including over-voltages in monolithic type PV-EC, photochemical degradation in PEC, erosion in liquid type PV-EC). To simplify construction, the development of PEC technology (EC-DSSC) seems promising.

Another problem is related to the glazing area. As the glazing surface area increases, the risk of technical issues arises. This fact offers a significant limitation in terms of the design of office windows. In this aspect, the development of PEC and liquid technology seems hopeful.

Depending on the number of EC phase transition cycles, the limited lifespan of systems that incorporate EC technology poses another challenge. This aspect seriously reduces the potential market attractiveness of this technology for office applications in moderate climates (frequent use of window adjustments should be assumed).

In the case of side-by-side systems, which also account for SPD and LCD glazing, additional technical and hardware requirements, i.e., the need to use inverters and electric batteries, are seen as a negative feature. In this sense, these technologies are perceived as less suited to cooperation with PV technology. The PV technology itself also faces technical issues. These problems mainly apply to 3rd generation cells (short service life of organic cells, instability of the DSSC and perovskite cells current-voltage parameters). Thus, at present, the entire integrated system of PV technology and switchable glazing cannot be considered reliable. Simpler side-by-side systems, understood as a combination of two relatively independent technologies, yield better results in this field.

TABLE 1. Tabular comparison between PV-powered switchable glazing technologies regarding their suitability for façade glazing of office spaces for moderate climates (by the author).

<table>
<tr><th rowspan="2"></th><th colspan="3">SIDE-BY-SIDE</th><th colspan="2">SOLID</th><th>LIQUID</th></tr>
<tr><th>EC-PV</th><th>SPD-PV</th><th>LCD-PV</th><th>monolithic</th><th>PEC</th><th></th></tr>
<tr><td rowspan="2">Ambient dispersed natural light access</td><td>• suitable (EC) in windows exposed to both sunny and cloudy weather and relatively constant lighting conditions;
• unsuitable when the color of light is a priority</td><td>• suitable (SPD) in windows exposed to solar light; especially right in dynamically changing lighting conditions</td><td>• unsuitable (LCD) in windows exposed to solar light
• suitable in shadowed parts of the building (provided that PV is exposed to solar light)</td><td colspan="2" rowspan="2">• can be compared with EC—PV systems: similar characteristics but currently the least suitable because of the lowest optical contrast and transparency</td><td rowspan="2">• can be compared with EC—PV systems: similar characteristics but currently less suitable than EC-PV side by side technology because of worse optical contrast and transparency and for the same reason slightly more suitable than solid type technology</td></tr>
<tr><td colspan="2">• most suitable in PV-EC/SPD façade/ window systems, in which PV is II or III generation solar cells
• most suitable in PV-EC/SPD façade/ window systems, in which EC/SPD is in charge of natural light access</td><td></td></tr>
<tr><td rowspan="2">Protection against heat and cold</td><td>• most suitable in windows as a part of passive solar gains strategy;</td><td>• most suitable in solar protection windows;</td><td>• unsuitable for solar heat protection</td><td colspan="2">• similar to EC-PV systems but currently the least suitable because of the worst operational behavior by low-temperature values and the smallest g-value range</td><td>• similar to EC—PV systems but better for solar heating and solar protection than PV-EC solid type systems</td></tr>
<tr><td colspan="6">• unsuitable as individual external windows/façade glazing with which to provide stable temperature parameters (dissatisfactory U value)—all the technologies have to be coupled in double or triple Low-E glazing units or/and double-leaf façades</td></tr>
<tr><td rowspan="3">Glare control</td><td>• suitable (EC) only when no need occurs for frequent switching between the off and on mode</td><td rowspan="2">• suitable (SPD) especially in dynamically changing solar radiation level</td><td rowspan="2">• unsuitable (LCD) in windows exposed to solar rays</td><td colspan="2">• similar to EC-PV side-by-side system</td><td>• can be compared with EC—PV systems: similar, but worse for the long transition time</td></tr>
<tr><td>• in practice extra shading system required</td><td colspan="3" rowspan="2">• in practice extra internal shading system required (external shading is unfavorable because of covering the PV layer in the EC-PV system)</td></tr>
<tr><td>• PV (opaque 1st–3rd gener. or semi-transp. 2nd–3rd gener. as solar shelve recommended</td><td>• SPD glazing rather than PV as solar protection partition recommended</td><td>• PV (opaque 1st–3rd gener. or semi-transp. 2nd–3rd gener. as solar shelve recommended</td></tr>
</table>

<table>
<tr><td rowspan="2">Privacy control and contact view with the surroundings</td><td>• suitable (EC) when contact view is a priority (however worse than the traditional window)
• unsuitable (EC) for privacy control</td><td>• suitable (SPD) when privacy control is a priority, although it is also suitable for contact view (more flexible adjustment than LCD)</td><td>• suitable (LCD) when privacy control is a priority, although it is also suitable for contact view</td><td colspan="3" rowspan="2">• can be compared with EC-PV side-by-side systems but provide worse contact with the surroundings because of the lack of visual uniformity (the connection between EC and PV within one product) and a negative impact on the focus of the outlook from the window.
• unsuitable for privacy control</td></tr>
<tr><td colspan="3">• PV 1st generation: suitable for privacy control only
• PV 2nd–3rd generation: suitable when privacy control is a priority, although in some cases of semi-transparent PV modules—as windows providing contact view possible (secondary role)</td></tr>
<tr><td rowspan="2">Energy efficiency</td><td>• very suitable (EC) in energy-saving concept</td><td>• suitable (SPD) in energy-saving concept but less favorable than EC for its electricity consumption in the off mode</td><td>• unsuitable (LCD) in energy-saving concept</td><td colspan="2" rowspan="2">• evaluation difficult: more investigation needed—similar but slightly smaller relevance to other PV-EC systems can be predicted, for their smaller solar power generation yield (in comparison with the application of non-transparent PV modules with I generations solar cells in PV-EC side-by-side systems) and lowest transparency that affects the relative higher need for electrical lighting</td><td rowspan="2">• like PV-EC solid, but a bit more suitable because of better transparency that affects the reduction of the need for artificial lighting</td></tr>
<tr><td colspan="3">• most suitable when coupled with the most efficient PV modules (non-transparent modules with I generation PV cells characterizing the highest power output relatively</td></tr>
<tr><td>Technical-utility reliability</td><td>• relatively suitable (EC) in rather constant lighting conditions; in dynamic weather conditions less suitable than SPD (limited lifespan due to frequent switching needs)</td><td colspan="2">• relatively suitable (SPD, LCD) but more prone to technical failures than EC when considered as PV-SPD or PV-LCD system (more complex technology)</td><td rowspan="2">• currently unsuitable: potential high risk of failure for glazing surfaces typical of windows and larger; surface limit</td><td rowspan="2">• currently unsuitable: similarly to monolithic PV-EC, though more promising due to the simplified structure and independence from the increase in the glazing area</td><td rowspan="2">• currently unsuitable:
• similarly to monolithic PV-EC, though more promising due to the simplified structure and independence from the increase in the glazing area</td></tr>
<tr><td></td><td colspan="3">• currently most suitable when coupled with I–II generation PV cells</td></tr>
</table>

4. DISCUSSION AND CONCLUSIONS

PV-powered switchable glazing technologies introduce new functional, behavioral, and ecological-energy qualities in shaping the office work environment. They may be seen as the next step in the evolution of the glass façades as an interactive partition intended to mediate external and internal conditions.

The improvement of functional quality concerning traditional (non-switchable) glazing is based on regulating light and solar heat access to the interior. This feature is of particular importance in buildings where the use of external mobile shading systems is impossible or inadvisable (e.g., in high-rise office buildings). The increase in operational quality is associated with the opportunity to regulate the degree of glazing transparency. Thus, psychophysical reactions of the employee related to the sense of privacy or maintaining eye contact with the environment can be influenced. The ecological-energetic value of such devices lies in the fact that they disburden energy-consuming HVAC systems. Simultaneously, PV-switchable glazing is energy self-sufficient, as well as it offers a possibility of generating surplus energy from the sun as a renewable energy source. All these three features correspond with the current trends in shaping office architecture.

Quality improvement in these three areas occurs jointly within one product or system, which is seen as the primary and distinctive advantage of PV-switchable glazing.

Since PV-switchable glazing combines the building envelope with installations, it breaks with the contemporary theory of the layered nature of a building developed by Francis Duffie and Stuart Brand. According to the theory, the building envelope and its installations constitute separate layers with different degradation times (Niezabitowska and Masły 2007). This highlights the need to standardize the aging time of the elements that make up the complex structure of the PV-switchable technology. This requirement applies, in particular, to the integrated technologies, both solid and liquid ones.

Essentially, none of the technologies discussed above can fully meet the requirements for office windows in a moderate climate. However, each of them offers strengths and weaknesses of its own. This research proves that the studied technologies are marked with diversified features. The side-by-side technology with EC and SPD glazing seems to be the most suitable at the moment, as it is based on relatively advanced switchable and PV glass technologies separately. LCD glass should not be analyzed in terms of its impact on the thermal and light environment. Therefore, unlike EC and SPD, it cannot constitute a part of the concept for shaping energy-saving and environmentally friendly architecture of offices.

Among the PV technologies in side-by-side systems, the 3rd generation modules may prove adequate in the conditions of direct insolation deficit (e.g., unfavorable orientation towards the outside environment). In these conditions, a lower loss of efficiency is observed for such modules. However, the efficiency of PV modules in PV-switchable windows, also in the energy aspect, is only a secondary feature. The prominent role of such devices results from the characteristics of PV cells related to the impact on the thermal and visual environment, as well as their lifespan and maintenance. For this reason, if the above features were considered together, it is advisable to recommend the 2nd generation semi-translucent cells, and in the future—once the disadvantages related to the lifespan are tackled—the 3rd generation cells. Semi-translucent PV modules with 1st generation cells should not be recommended due to their negative impact on the lighting environment (contrasts, glare effect).

The advantage of the side-by-side technology over the integrated technologies (solid and liquid ones) arises from the fact that side-by-side technology consists of two components that can be better adapted to their function (e.g., switchable glazing as a light barrier, PV as a solar protection shelf). However, in the case of SPD and LCD glazing, the complex structure of the entire system (including the requirement to use inverters and batteries) may be seen as a disadvantage. EC technology powered by direct current supplied directly from PV modules and in the transparent off-mode (with no electricity) should be considered better suited to work with PV technology. Moreover, such a solution is more appropriate for use in a moderate climate, where the need for solar protection is relatively low compared to warmer climates. Another advantage is related to greater transparency and greater activation range. The main disadvantage of the EC technology lies in the lengthy phase transition period, unnatural and non-uniform coloration, and limited service life—in the context of applications in office windows, SPD glazing offers a significant advantage in this field.

Integrated technologies, both solid and liquid, demonstrate the most complex construction and installation solutions for façade glazing within an individual building element. Such a design increases the risk of potential failures and renders repair difficult. For this reason, at the present stage of development, they should be considered less attractive compared to side-by-side technology, although the latter is more complex as a system. Other significant barriers to applying integrated technologies for office windows glazing include their low transparency and low activation range. The greatest potential to overcome the obstacles to glazing translucency and the activation range should be associated with the liquid technology. In turn, the most significant advantage of PEC technology is its simplified structure. Both PEC and liquid technologies are characterized by the independence of functional properties from the surface. This advantage may prove decisive in the future for façade applications in offices and other buildings. Combining these advantages in one product while eliminating the phase transition heterogeneity and the problems related to overvoltage, aging, and corrosion should be considered as the proper development directions for integrated technologies; relying on EC technology seems appropriate for moderate climate applications.

All the technologies discussed above cannot serve as separate building elements. This feature results mainly from their thermal aspect—the need to connect them with appropriate glazing units with the required U coefficient. PV-powered switchable glazing as an external coating in double-leaf façades is particularly advantageous in this field. The inter-cover space, which acts as a thermal buffer, can neutralize the adverse effects of heat emission to the environment from the glazing surface. As in analogous solutions with PV glazing, heat can be used to stimulate displacement ventilation. At the same time, the inter-cover space offers a good place for installing additional solar protection elements (e.g., blinds), which would be desirable in the case of solutions with EC technology due to its long phase transition time. This solution also eliminates the disadvantage of monolithic and liquid technologies—in single leaf facades, the use of external solar protection systems is irrational due to the shading of the photovoltaic layer.

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