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THEORETICAL MODELS OF PV-EC WINDOWS BASED ON THE ARCHITECTURAL ANALYSIS OF PV-EC TECHNOLOGIES

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Abstract

The paper provides an architectural analysis of the switchable PV-EC glazing technology based on combining photovoltaic (PV) technology with electrochromic (EC) glazing. The integration of these technologies is considered to constitute future-oriented façade solutions in shaping buildings that are energy-saving and environmentally friendly. The paper aims to define theoretical models of windows using PV-EC technology as solutions adequate from the architectural point of view. To achieve this goal, a comparative analysis of three PV-EC technologies was conducted, i.e., side-by-side (SBS) technology and tandem technologies, namely tandem solid technology (TST) and tandem liquid technology (TLT). The analysis covered functional aspects related to such issues as thermal and visual comfort, energy and aesthetics. The analysis led to extracting the features of the three compared technologies; consequently, their strengths and weaknesses were determined. As a result, seven window models were developed which, based on the above analysis and the insights derived from it, were recognized as the solutions in which the potential of PV and EC technology is best used. The dominant advantages of SBS, being the most developed technology and one with the greatest flexibility in construction applications, are indicated. The research is of a contributory nature, as it constitutes the basis for further numerical and simulation research. Such studies may prove useful to architects in making design decisions, especially at the initial design stages. However, at the current stage of technological development, the study mainly serves as an introduction to further research on improving the PV-EC properties towards integration with the building and its architecture.

Keywords: **PV-EC, switchable glazing, PV glazing, BIPV, smart windows, energy efficient buildings, green architecture**

1. INTRODUCTION

Contemporary pro-ecological architecture is searching for solutions with which to reduce the building's energy consumption, while maintaining its high utility quality. Façades provide barriers between the different conditions of the external and internal environment. As such, they become an important element in achieving this search. The technological development of façade partitions leads to the formation of the so-called responsive façades [1], which are assumed to adapt their parameters to the current external conditions, thereby improving the building's energy balance and the internal space use comfort. Switchable glazing technologies are seen as one of the most interesting groups of responsive façades. They are defined as glazing that has the ability to change its optical parameters in a controlled manner. Most of these technologies require electricity. This is where the merger between switchable glazing technology and photovoltaic (PV) technology occurs. Solar cells that generate electricity from sunlight are considered a solution with which to support the work of switchable glazing, to make it self-sufficient in energy terms , thus in line with the idea of shaping energy-saving architecture.

The extensive analysis of the PV-switchable technology conducted earlier by the author revealed that, at present, the use of electrochromic glazing is most advantageous in the construction application context [2]. One of the advantages lies in no need for electric current conversion – both technologies operate on direct current, which reduces the need for inverters. Another advantage is the fact that the EC technology

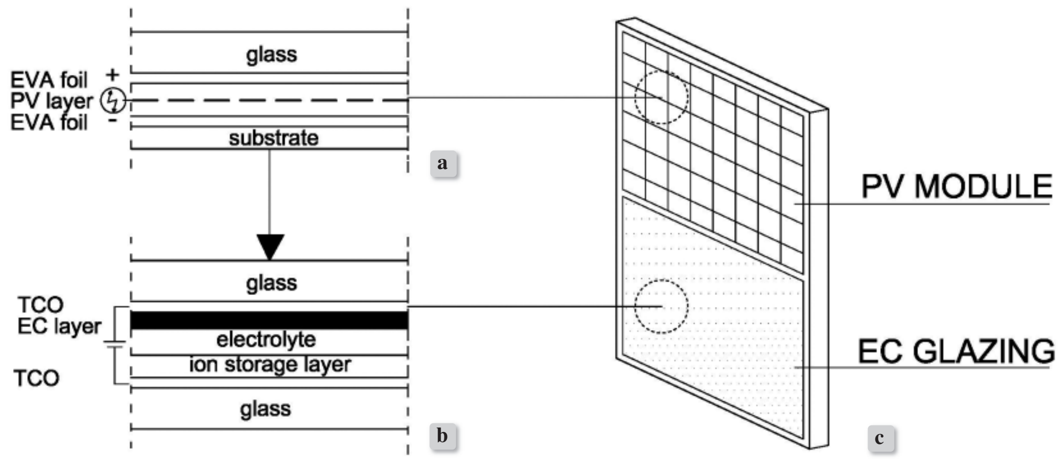

Figure 1.
PV-EC side-by-side (SBS) technology: A – typical PV module, B – EC glazing, C – exemplary configuration of PV-EC in SBS [by the author]

remains one of the most commercially developed switchable glass technologies, thereby offering products suitable for use in windows and façade systems. Studies have been conducted for many years and they indicate the utility benefits of EC glazing, e.g., [3], as well as its energetic qualities, e.g., [4], as compared to static glazing.

These observations prompted a closer focus on the current technological concepts of combining EC glazing with photovoltaics in façade applications. The paper aims to define theoretical window models with PV-EC technology as solutions adequate from the architectural point of view. In order to achieve this goal, a comparative analysis was performed of three PV-EC technologies, which are currently known and are in the research phase. These include side-by-side (SBS) and tandem systems, both solid (TST) and liquid (TLT). A comparative analysis was conducted in the aspects important from the architectural and design point of view, i.e., utility related to thermal and visual comfort, energy and aesthetic issues.

2. GENERAL CHARACTERISTICS OF THE PV-EC TECHNOLOGY

2.1. Side-by-side technology

The side-by-side (SBS) technology creates a system characterized by the configuration of the EC glazing and the photovoltaic element in the form of two separate components. In the case of façade applications, the technology may be applied in the form of a window or a glass façade system composed of two parts, one of which is EC glazing, whereas the other is a PV module (Fig. 1). This module supplies EC glazing as an individual component, which distinguishes the solution from tandem technologies [5]. For this reason, the selection of PV cell technology is nearly unlimited. Theoretically, the solution can comprise mono-polycrystalline silicon thick-film cells, second-generation thin-film cells, including amorphous silicon, CdTe, CIS cells, as well as the most recent, third generation cells, inclunding organic, DSSC and perovskite cells. Under the influence of electric voltage, a chemical reaction in the EC glazing takes place. The ions drain from the electrochromic (active) coating into the ion storage coating, thus, the former and, consequently, the entire EC pane, is darkened. By reversing the direction of the electric field, thanks to the transparent electrodes (TCO), the ions return to the active coating and the pane becomes transparent again.

2.2. Tandem solid type (TST) technology

Tandem solid-type (TST) technology is a system composed of combined, superimposed EC and PV technologies in a single product, also called monolithic PV-EC (fig. 2a) [6]. For this reason, the TST technology is characterized by a complex multi-layer structure surrounded by transparent electrodes and a traditional glass casing. TST technology is still at the research stage. Various technologies of thin-film and third generation cells are being tested [7]. In the basic solutions, amorphous silicon cells are applied. The PV layer is placed on the underside of the EC layer. Progress is being made towards simplifying the product's design. The most interesting concepts include

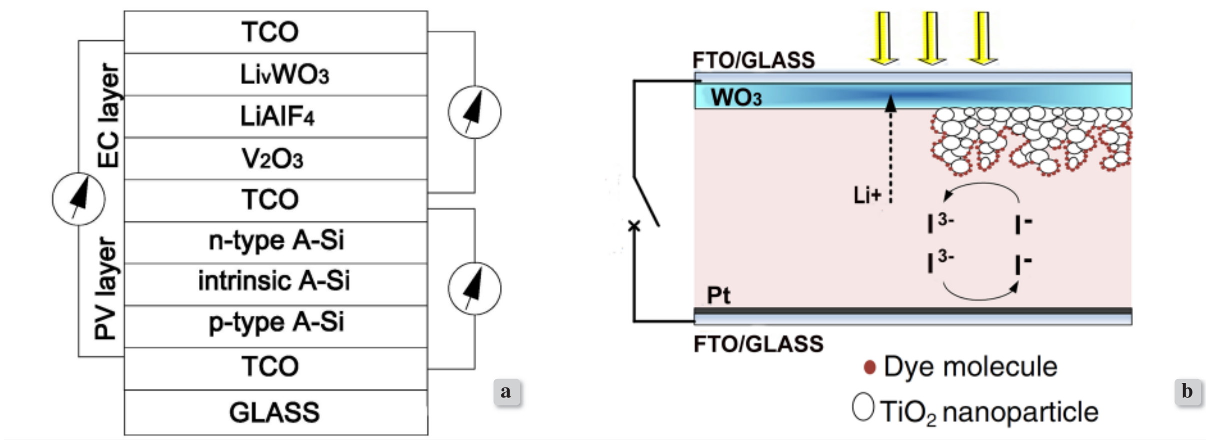

Figure 2.
PV-EC solid types technologies: A – monolithic tandem structure Si-based PV-EC [6] B – PEC technology [9]

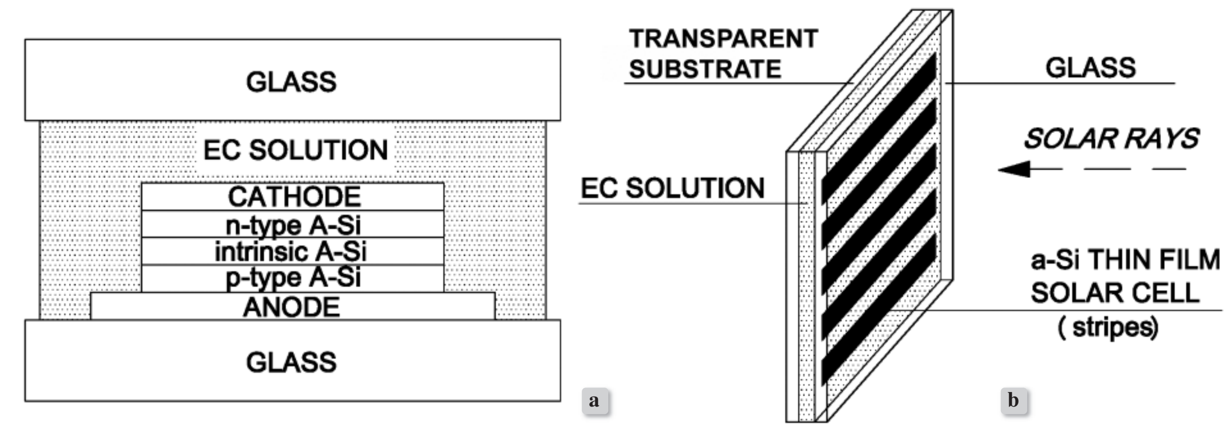

Figure 3.
PV-EC liquid (solution) type technology : A – section B – elevation [9]

the photoelectrochromic (PEC) glazing technology, in which the EC layer is surrounded by a PV layer composed of DSSC cells (Fig. 2b) [8].

2.3. Tandem liquid type (TLT) technology

The liquid type (TLT) technology, like the TST described above, is a tandem technology. The main difference is the electrochromic material, which here comes in a liquid form. This translates into the construction of a PV-EC system. PV cells are somewhat immersed in the EC solution. The system (combined PV and EC layers) is surrounded by nonconductive transparent substrate and the traditional glass (Fig. 3). Like the TST technologies, the TLT is still being tested and researched. The basic photovoltaic material comprises translucent amorphous silicon cells. However, other thin-film cells – CIGS and CdTe, are also being tested [9].

3. ANALYSIS OF THE PV-EC TECHNOLOGY PROPERTIES

The analysis of the PV-EC technology properties was conducted concerning the aspects seen as valid from the architectural design point of view, i.e., thermal behavior, optical behavior (lighting protection and visual contact), utility and energy behavior, aesthetic variability. Efforts were made to determine the most important features by presenting them in a simplified manner, so as to make the study useful for designers. Therefore, the decision was made. to resign from specialist, detailed technological analysis.

3.1. Thermal behaviour

In the SBS configuration, the thermal characteristics of both PV and EC technologies are not directly related – both technologies can, therefore, be considered separately.

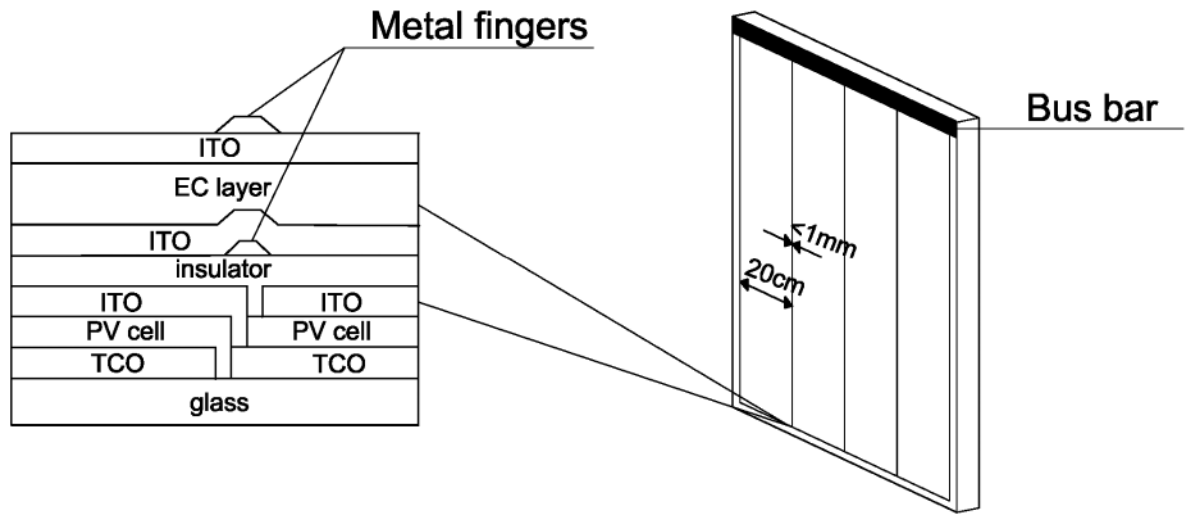

Figure 4.
Structure of a large-area monolithic PV-EC glazing [6]

The EC glazing reduces the solar radiation through absorption, and, to a lesser extent, by reflection. Therefore, this form of glazing tends to heat up. The thermal load accumulated on the surface of the façade panes poses the risk of heat emission to the building's interior and, consequently, to its overheating. Individually, commercial EC panes do not meet the requirements in terms of thermal insulation. Therefore, they need to be combined into window sets, most often double-glazed (DGU) and triple-glazed (TGU) sets. Such glazing is also used in sets with a low-emission (low-e) coating and vacuum glazing. The obtained U coefficient remains in the range of 0.5-1.7 W/(m^2K) [10].

PV modules have similar characteristics. Their operation is also based on the phenomenon of solar radiation absorption. However, the generation of heat comes as a side effect of the photovoltaic conversion. Hence, for the same reason, the PV façade glazing requires the use of glass with increased thermal insulation.

As solar control glazing, the EC glazing, has the ability to control the total solar energy (g) transmittance parameters which is its characteristic feature (as in the case of any switchable technology). The EC glazing reaches g-factor values in the range of 0.05–0.6 in the state of maximum darkening (active state) and bleached (passive state), respectively [4].

In tandem PV-EC configurations, the thermal characteristics overlap, which results from the integration of these two technologies in one product. Therefore, both the EC and PV layers emit the heat. Certain discrepancies between the EC and PV technologies in their response to high temperature occur, which may lead to potential problems. In the case of silicon cells, the increase in temperature at their surface is a negative phenomenon, as it causes a decrease in the cell's efficiency in terms of electric current and processing. The EC layer, on the other hand, displays a more rapid phase change with increasing temperature, i.e., transition between active and idle states. The functioning of the EC pane as a solar control pane is, therefore, more effective. Thus, in conditions of low temperature amplitude and its high value, it can be assumed that the PV and EC layer heating is a favorable phenomenon, as it is also associated with a lower electricity consumption. In the case of TST technology, this factor enables the thickness of PV cells to be reduced. This results in greater transparency of the PV-EC set.

In the case of TLT technology, the thermal behavior is currently relatively unrecognized. It can be assumed that it is similar to that of the TST, but the greater optical contrast (see section 2.2.) suggests that it may be better suited as a solar control measures in glass façade partitions.

3.2. Optical behavior

As in thermal aspect, the optical behavior of the SBS configuration needs to be discussed separately for the PV and the EC technology.

The optical characteristics of PV cells vary. Thick film cells are opaque, whereas partial transparency of PV modules is achieved by separating the PV cells within them. Such modules are used as façade and roof glazing. They ensure the supply of natural light to the interior in an amount depending on the spacing of the PV cells. Eye contact with the surroundings is difficult. In a sunny weather, such modules generate strong light and shade contrasts in the room.

The technology of thin-film and third generation PV cells allows for the creation of homogeneous semi-transparent modules. Eye contact is possible, although certain reduction in sharpness and a discoloration of the image occurs. The inflow of visible solar radiation to the interior ensues in the form of scattered light.

Commercial EC glazing operates in the range of 3.5–65% [3] light transmittance (Tv), although it is possible to obtain larger spans: 1–70% [11] or 6–76% [12] for darkened and clear states, respectively. It is possible to obtain intermediate parameters, as well. In the bleached state, the EC glazing is slightly yellowish in color. When completely darkened, it turns dark blue as a standard, though these colors may differ (see section 3.4.). The image sharpness and color are reduced, but the user's eye contact form inside the building is maintained.

The differentiation between the PV and the EC features is the reason why technological difficulties emerge in tandem configurations. The PV-EC glazing in the TST technology requires the thinnest possible PV layer in order for the transparency of the set to be increased. In the standard TST solutions, an insulating layer is required on the joining of both layers (the EC and the PV) to prevent potential shortcuts. This layer requires bus-bars and metal fingers (Fig. 4). These elements, visible in the PV-EC glazing, make the glazing surface not homogeneous, thereby disrupting the unlimited visual contact with the surroundings. Yet, research shows a fundamental acceptance of this feature among users.

However, the TST technology poses a serious problem when it comes to the modest switching span in light transmission. The Tv coefficient in the set with perovskite cells remains within the range of 8.4% and 26% [13]. In PEC technology, this range is slightly higher - the difference in Tv value between clear and darkened states is approximately 30%. Another problem is related to the heterogeneity of the transition phase, namely, dimming is slow and heterogeneous. This issue becomes more pronounced with increasing the PV-EC glazing area and occurs with applications corresponding to façade glazing (e.g., 1 m^2). The color of the glazing in the TST technology is similar to that of the individual EC panes. When lightened, the glazing is characterized with a yellowish tinge. In the dimming state, it takes the basic dark blue color.

Against the background of the TST technology, the TLT technology seems an improved solution. Due to the possibility of thinning the PV layer, the TLT is distinguished by a higher translucency as well as by a much higher optical contrast that amounts to 70% [9]. This technology eliminates bus burs and metal fingers, but TLT technologies come with characteristic stripes on their surface, which also makes it visually not homogeneous. No data on the effect on eye contact is available.

3.3. Utility and energy behavior

In the discussed aspect, the PV-EC glazing can be divided into two functions: power generation by the PV cells and optical activity, i.e., switching between the idle and active states of EC glazing.

PV cells generate direct current (DC). To power the electrical equipment in a building, PV systems require inverters to convert it into alternating current (AC). However, inverters are unneeded to power the EC glazing, which also operates on direct current. In this aspect, the EC glazing is at an advantage over competing switchable technologies, such as SPD (suspender particle devices) or LCD (liquid crystal devices), which require alternating current. The efficiency of the PV cells' energy performance is the most important parameter. The second generation PV cells have the highest efficiency, up to 25% in commercial applications [14]. Similarly, thin-film cells are characterized by efficiency at the level of several percent [15, 16] whereas the third generation cells (DSSC and organic) usually do not exceed 10% [17, 18]. Perovskite cells (PSC) technology, which remains mainly in the laboratory testing phase is regarded as a promising technology that can obtain a much higher efficiency (exceeding the efficiency of the first generation cells). However, it is pointed out that there is an urgent need for standardizing the measurements of the PSC modules' aging and efficiency by establishing a reliable and transferable methodology so as to correctly reflect the device's true performance [19].

In terms of energy behavior, the silicon cells, mainly of the first generation ones, are susceptible to temperature increase. Their efficiency drops by $0.5\%/\Delta T = 1°C$ [20]. This phenomenon is not observed in the case of other PV cells, whereas in the case of the DSSC, the opposite situation occurs- an increase in temperature upsurges their efficiency [21]. The advantage of the third generation cells lies also in a lesser dependence on the orientation towards the corners of the world, i.e., such cells are characterized by a relatively higher efficiency of photovoltaic conversion of scattered light.

The EC glazing requires a voltage of up to 10 V in order to enter the active phase. Solutions are being tested in which the EC glazing, similar to batteries, has the ability to store electricity, i.e., the so-called electrochromic energy storage devices (EECD) [22]. Nevertheless, the advantage of all PV-EC configurations results from the convergence of electricity generation and operation of the EC panes. Due to the low energy requirements, the efficiency of the cells in the PV-EC set seems to be of less importance. From the operational point of view, the EC glazing transition time is more important. In individual applications, i.e., their SBS configuration, the transition to the complete darkening phase takes from a few to about 20 minutes, with the phase change span being directly proportional to the glazing area. It is the longest transition time among all switchable glasses [2].

In the tandem TST configuration, the glazing behavior of the PV-EC is similar to that of SBS. However, this applies to the traditional (monolithic) TST technology, i.e., with piled-up EC and PV layers based on amorphous silicon. The PEC technology is characterized by the independence of the transition time from the glazing surface, which is promising for large-area façade applications [8]. The disadvantage, however, is the lower stability of the PEC [23]. On the other hand, in the case of the monolithic technology, due to its very high degree of complexity, a greater risk of short-circuits arises. This risk grows along with the increase of the glazing surface. Another potential problem, not present in the case of the PEC technology, is the cooling of the silicon cells' surface. This problem is more difficult to solve than in the case of the SBS configuration.

In laboratory tests, the TLT technology requires approximately 3–5 minutes until the solution goes completely dark. Due to its structure, similarly to the PEC, the transformation time does not depend on the glazing surface. There is also no problem with heterogeneous color. Therefore, these features appear promising in the context of façade applications [9], but the transition time is still considered too long [7]. Moreover, the TLT technology reduces the risk of short-circuits [6], while the problem of the rapid degradation resulting from erosion on silicon layers emerges [24].

3.4. Aesthetic variability

When considered separately, the PV and the EC technologies differ significantly in terms of aesthetic diversity.

The PV technology, is strongly established in the construction market. Over the years, a very wide range of PV cells and modules with an unlimited palette of colors, textures and elevation drawings as well as various transparency (as part of photovoltaics integrated with the building – BIPV) have been developed. Basically, the appearance of the PV cells as such depends on the semiconductor material used. In their natural form, the first generation PV cells (silicon, thick-film) are black or dark-navy blue; these differ in texture. In the navy blue polycrystalline cells, sparkling crystals are visible, which is their characteristic aesthetic feature. The thin-film cells take various shades of black and dark gray, whereas their surface is homogeneous, matt. The third generation cells are generally produced in dark colors, but unlike other types, they can have different colors depending on the dye used in their structure. In the case of the PV modules made of first and second generation cells, their color, texture and drawing are determined by films applied in various configurations to the glass elements of the module or the PV cells themselves [25] and by other elements, such as e.g., aesthetic features of the substrate, electrodes and their display, module frame. It is possible to obtain cells of different colors, also within a single module. Modules similar to traditional building materials are possible as well (e.g., bricks). The PV glazing made of second generation cells is more homogeneous, but laser cuts are generally visible. The modules of third generation PV cells take a completely homogeneous form, similar to that of the solar glazing. The aesthetic variety of the PV technologies has been described in detail, e.g., in [26, 27].

Compared to the aesthetic variety of the PV technology, the EC glazing has less advantageous characteristics. In its basic form (i.e., where the EC material is tungsten trioxide (WO_3), the darkened-phase glazing has a dark blue (Prussian blue) tint. In the clear state, it is neutral in color, with a yellowish tinge. The use of other materials makes it possible to obtain other tints of the glazing in the darkened phase, e.g., bronze (NiO) and black (IrO_2). Solutions for changing the available colors are also being tested, such as red-blue (CoOx) or yellow-green (Rh_2O_3) [28]. In the case of the EECD glazing in window applications, in addition to the standard color of the active phase, i.e., Prussian blue, a green color is available [22].

The above aesthetic differentiation can be related to the SBS configuration of the PV-EC glazing.

The review of research on tandem configurations shows that the discussed differentiation is much poorer. Tandem configurations, which still remain mainly in the research and testing phase, are based on the basic, most typical materials and have not entered the phase of expanding the aesthetic offer. The TST technologies, based on WO_3 as the EC coating material, assume a dark navy blue color in the darkening state. In large-area applications, the need to add bus-bars and metal fingers is indicated. No studies on the effect on the aesthetics of the PV-EC glazing are available, although it can be assumed that such a solution may resemble strings in the PV modules. The Fraunhofer Institute presented yellow PEC samples. The technology based on the DSSC dye cells, due to the specificity of these cells, may offer greater possibilities in the color range of the PV-EC glazing. In order to obtain a homogeneous color (also dark blue), the TLT technology is characterized by distinctive stripes. These are dark-gray, opaque electrodes, presented as 5 × 5 cm samples [9]. Due to the unlimited surface glazing possibilities of this solution, it can be assumed that this texture will be duplicated in the façade applications. Further research is required in this area.

Table 1.
Assessment of functional, energetic and aesthetic features of the PV-EC technologies: the SBS, the TST and the TLT in terms of their architectural and construction application – a comparison [by the author]

<table>
<tr><th></th><th>SBS</th><th>TST</th><th>TLT</th></tr>
<tr><td rowspan="3">Thermal comfort</td><td colspan="3">– both PV and EC behave like absorption glazing – a risk of heat emission to the interior arises and, as a result, overheating of the rooms is possible;
– required application of the PV and the EC in glazing units with increased thermal insulation in order to reduce the “mixed-mode” effect - uneven temperature distribution in the room; regardless, the lowest achieved U parameters in single-leaf glazing units do not equal solid façades.</td></tr>
<tr><td rowspan="2">– the EC is suitable as solar control glazing, but a slow phase transition causes it to lose its effectiveness in conditions of dynamic changes in sunlight; thus, additional support is required, e.g., the use of blinds;
– PV elements as non-regulated elements are less flexible, but they can provide permanent solar control measures.</td><td>– in practice, a slow phase transition in conditions of low outside temperature, makes it difficult for the TST to function as solar control glass – for this reason, the TST is the least suitable for façade applications in cool climates with a large number of sunny hours.</td><td>– the lack of adequate research, but a higher and faster phase transition than that of the TST makes the TLT more suitable as solar glazing.</td></tr>
<tr><td colspan="2">– no possibility to apply additional external solar protection elements due to unfavorable covering of the PV layer.</td></tr>
<tr><td>Visual comfort</td><td>– considerable flexibility in adjusting the EC and the PV to the requirements related to the lighting management of the room, i.e., the regulation of the sunlight supply (lighting vs glare protection);
– the EC glazing provides visual contact with the surroundings, acting as a light access regulator – suitable for use at the user’s eyesight level, however, the slow phase transition (proportional to the surface of the glazing) may require additional glare protection, e.g., blinds, roller shutters;
– the PV elements interfere with the eye contact with the environment, in the case of first generation cells, they do not allow an even supply of natural light (they obstruct the inflow or cause light and shade contrasts) – the second and the third generation translucent cells are suitable for glare protection (unlike modules with first generation solar cells), while providing the room with additional lighting.</td><td>– problems with obtaining transparency and color uniformity that would not cause visual discomfort, an additional negative factor may be the visible insulation elements in monolithic technology;
– unsatisfactory, low Tv values, owing to which the TST glazing seriously limits the access of daylight to the room;
– similarly to the SBS and the TLT, the long phase transition requiring the introduction of additional glare protection elements;
– size limitations of the PV-EC glazing, due to the increase of the phase transition time with the increase of the surface area (related to monolithic technology); in the case of PEC technology, independence of the glazing size from phase transition time – potential use of façade glazing.</td><td>– improved properties compared to TST in terms of the Tv value range; which enable the use of the TLT glazing in rooms requiring both natural lighting and protection against its excess (unlike the SBS);
– the size of the TLT glazing surface is independent of the phase transition time (unlike TST-PEC) – possibilities of the use of large-area façade glazing;
– the characteristic stipes may be a factor that distorts eye contact with the environment more than the insulation elements in the TST monolithic technology (further research required).</td></tr>
</table>

Energy-efficiency	All PV-EC configurations are energy self-sufficient, and, therefore, prove consistent with the idea of energy-efficient buildings. Low energy demand in relation to the energy gains given in the research resulting from the performance characteristics of the PV-EC [29].		
	– flexibility of the PV and the EC configurations offers optimization of protection against overheating (support for HVAC systems) with simultaneous natural lighting of rooms (reduction of electric lighting); – the simplest technologically in the discussed configurations - the lowest risk of damage (e.g., overvoltage); – the greatest possibilities to select the PV technology (impact on energy gains from insolation); – possibility of using the surplus electricity obtained (when supplying electrical devices – the application of inverters required).	– protection against overheating (support for HVAC systems), but reducing the access of daylight (increased demand for electric light compared to the SBS and the TLT); – the most complex structure (referred to monolithic technology mainly) - the greatest potential risk of damage (short-circuits); – the use of the PV is practically limited to supplying the PV-EC glazing.	– similar to the TST, but higher Tv values suggest a more favorable effect on reducing artificial lighting in rooms; – a less complicated structure than that of the monolithic TST carries a lower risk of electrical damage.
Aethetic function	– the possibility of matching the aesthetic features of both technologies; – practically unlimited color palette, texture and graphic effects of the PV elements; – relatively large variety of colors of the EC glazing compared to the TST and the TLT, but much poorer than the PV; – therefore, the PV should be treated as a component of the SBS, which can determine the contrast or relative aesthetic homogeneity of the SBS set - generally satisfactory possibilities of shaping the façades' aesthetic function, mainly in scope of the color palette.	– no possibility of aesthetic matching of the PV and the EC technologies (the PV should be as color-neutral as possible); – due to the fact that the TST and the TLT are still being tested, aesthetic matters, including color diversity, are not a priority at the moment; – limited color palette (mainly dark blue when darkened); – problems with obtaining a homogeneous appearance of the glass to make it look like glazing without the PV.	

4. ARCHITECTURAL EVALUATION OF THE PV-EC TECHNOLOGIES

The comparative summary presented in the table 1 indicates clearly that, at present, tandem technologies are not fully developed to be introduced to the construction market in the form of windows and other glass façade partitions. The greatest difficulties result from the inability to reconcile various properties of the PV and the EC layers into one, highly translucent product. As in SBS, the thermal and lighting behavior requires, support from additional solar energy control elements (heat and sunlight). Due to the need to expose the tandem PV-EC panes to the sun (exposure of the PV layer), the use of external blinds seems the most effective in terms of thermal protection. The dependence of the transition time on the glass surface is seen as the most significant obstacle in construction applications of the monolithic TST technologies. Additional problems lie in low translucency, a small range of light transmittance in the neutral and active state, as well as susceptibility to damage resulting from the complex structure of the entire set. Against this background, the TLT and the TST-PEC technologies seem more promising. Apart from the improvement of technical and operational features, all tandem technologies require an increase in diversity and aesthetic attractiveness.

The advantage of the SBS configuration results from the significant independence of the PV and the EC technologies, which gives the PV-EC set enough flexibility to adapt to the use requirements. Basically, the EC glazing is predestined to act as an illuminating, solar control coating, which, at the same time, ensures visual contact with the surroundings. The PV elements are generally less suitable for the latter purpose. For this reason, it appears that the EC pane should be given priority in a location at the user's eye level if an outward view is desired. The semi-transparent PV modules equipped with second and third generation PV cells are more advantageous than the thick-film cells in terms of even distribution of natural light, as they act as a solar filter. Due to the low power demand of the PV-EC set, the lower energy efficiency of the second and third generation cells is of minor importance.

The main problem with all PV-EC technologies results from its potential impact on room overheating. Apart from single-coat insulation sets, it seems reasonable to use the PV-EC panes as external coatings in double-leaf systems. The inter-shell void provides an additional thermal insulation factor, whereas the heat gains from the PV-EC surface can be used to support heating systems. It is also an attractive space for introducing additional elements to control the sunlight inflow, e.g., venetian blinds. In the case of single-leaf systems (similarly to the static glazing), it is not possible to achieve U parameters at the level of an insulated solid wall. The installation of the PV-EC panes is, therefore, more advantageous than all-glass façades in terms of thermal comfort and energy efficiency (likewise in the static glazing).

A significant advantage of the PV-EC configuration lies in the potentially wide range of aesthetic possibilities. Connecting the PV and the EC in independent window sections offers a wide range of color combination possibilities. In the case of the PV, diverse textural and graphic combinations are possible, ranging from relatively homogeneous solutions (complete homogeneity of the SBS seems difficult to achieve) to intentional contrasting.

5. THEORETICAL MODELS OF PV-EC WINDOWS

Based on the conducted architectural evaluation, recommended PV-EC glazing configurations for windows in building's façades were defined (Fig. 5). The presented theoretical solutions are based on the assumption that the PV-EC glazing will be used in insolated façades (eastern, southern and western), i.e., where its use is sensible. It was also assumed that the building façades require thermal protection both in the summer (the risk of overheating) and during heating periods (the risk of thermal lost). Therefore, the façades most closely correspond to the moderate climatic features.

It was also assumed that the need to ensure eye contact with the surroundings and a high-quality visual environment provide important design elements. Such assumptions can be attributed to office rooms. Hence, the following models have been developed with these rooms in mind.

The models represent seven different solutions for office facades in temperate climate. Each of them, according to the author, makes the best use of the discussed PV and EC technologies

It was established that the SBS configuration in two main groups of solutions, namely single leaf glazed partitions (A-C) and double leaf façades (D-F) may be recommended. In the case of A-C, the partitions in form of windows rather than fully glazed walls are preferable (see section 3.). A configuration with tandem PV-EC technology (TST-PEC or TLT) (G) was also proposed, although given the contemporary technological level it should be treated as theoretical solution that assumes overcoming the technical problems described in the analysis.

Fig. A: Single-leaf window/façade: PV: solar window (module) made of second or third generation PV cells as BIPV constant shading device that protects against excessive solar light in warm seasons.

EC windows as a partition to regulate the access of heat and sunlight, as well as visual contact with the surroundings. Possible passive solar gains during heating seasons. A highly thermally-insulated window set (~0,5 W/(m^{2}K)).

Fig. B: as above, but PV in the form of a solar shelf - slant more favorable in terms of solar protection and solar energy gains (unfavorable solution in high-rise buildings).

Fig. C: as Fig. A with an additional lower (floor-mounted) PV module. Due to its limited impact on the visual environment - the possibility of its use as solar window made of first generation PV cells.

Fig. D: derivative of Fig. A in the double-leaf façade variant. PV and EC constitute the outer pane, whereas inner window is neutral (traditional) highly-insulated pane assembly. In the inter-cover space (air void), an alternative to introducing shading systems (e.g. venetian blinds) to optimize the regulation of sunlight inflow to the interior. Air circulation cools the surface of the EC and PV, both of which emit heat into the inter-cover space. During heating periods, this space creates an additional heat buffer. Moreover, warm air can be used to support the heating systems of the building. In warm periods, heat emission stimulates the operation of displacement ventilation, which positively influences the cooling capacity of offices (e.g. in the night ventilation strategy).

Fig. E: as Fig. D, but with an adjustable (openable) top PV shelf. A more advantageous solution in terms of effective ventilation of the inter-cover space, solar protection and energy gains from insolation (a disadvantageous solution in high-rise buildings).

Fig. F: as Fig. D, but with an additional lower (floor-mounted) PV module. Due to its limited impact on

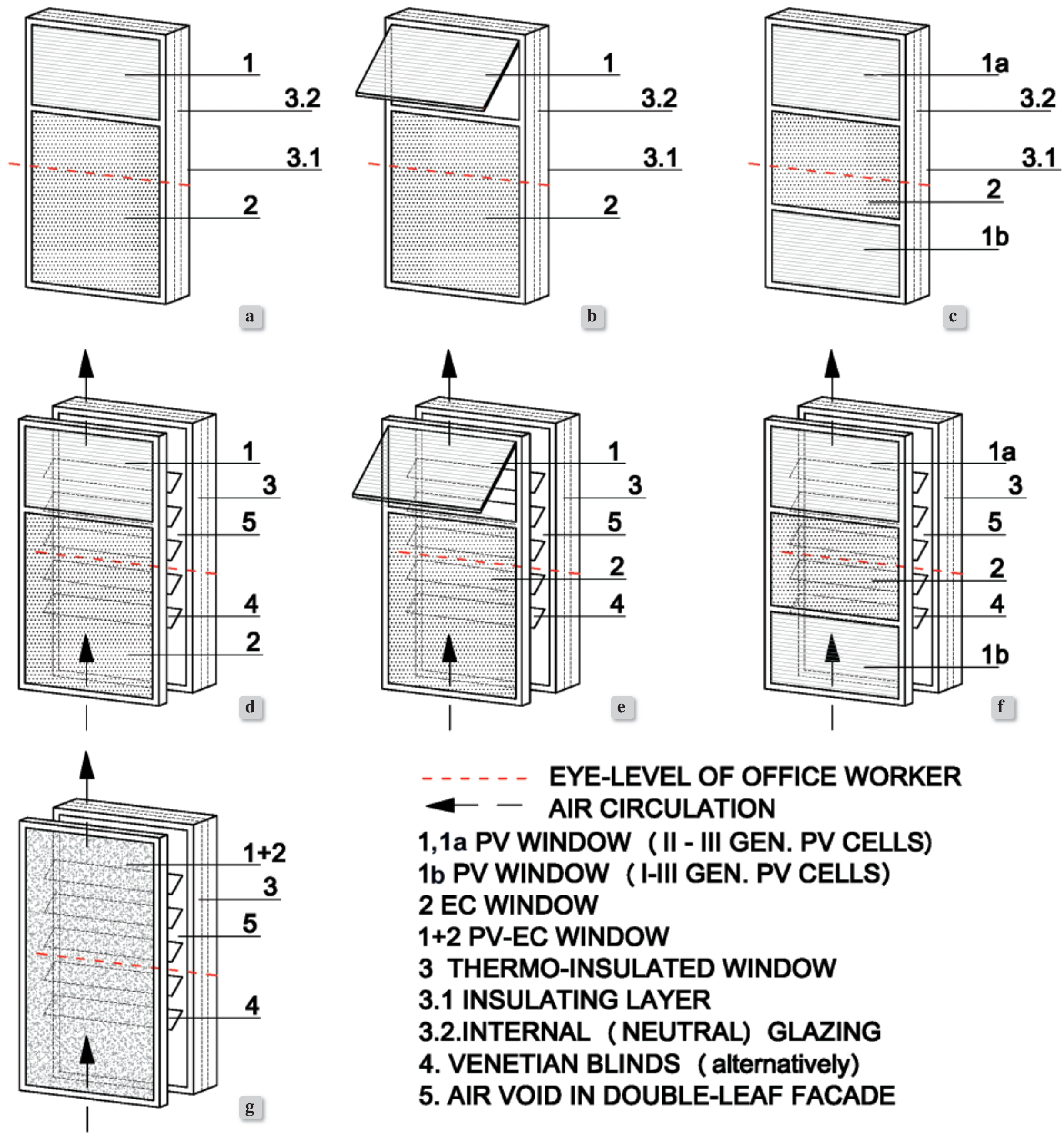

Figure 5.
Recommended configurations of PV and switchable glazing (by the author)

the visual environment – the possibility of its use as solar window made of first generation PV cells.

Fig. G: Double-leaf façade configuration (like in D-F) with integrated PV-EC technology (solid or liquid) as outer leaf. The main advantage of this configuration lies in a simplified construction of the entire glass partition. The solution includes such advantages as an improvement in optical properties of PV-EC glazing related mainly to its translucency.

Based on the C model (Fig. 5), an attempt was made to show the aesthetic potential for shaping color and graphic effects on façades using the PV-EC technology in the SBS configuration (Fig. 6). It was adopted assumption that the EC glazing has the basic color - i.e., Prussian blue. The aesthetic potential lies in the color and graphic differentiation of the PV modules' surfaces. An additional factor, not visible in the above diagrams, is the gradation of translucency.

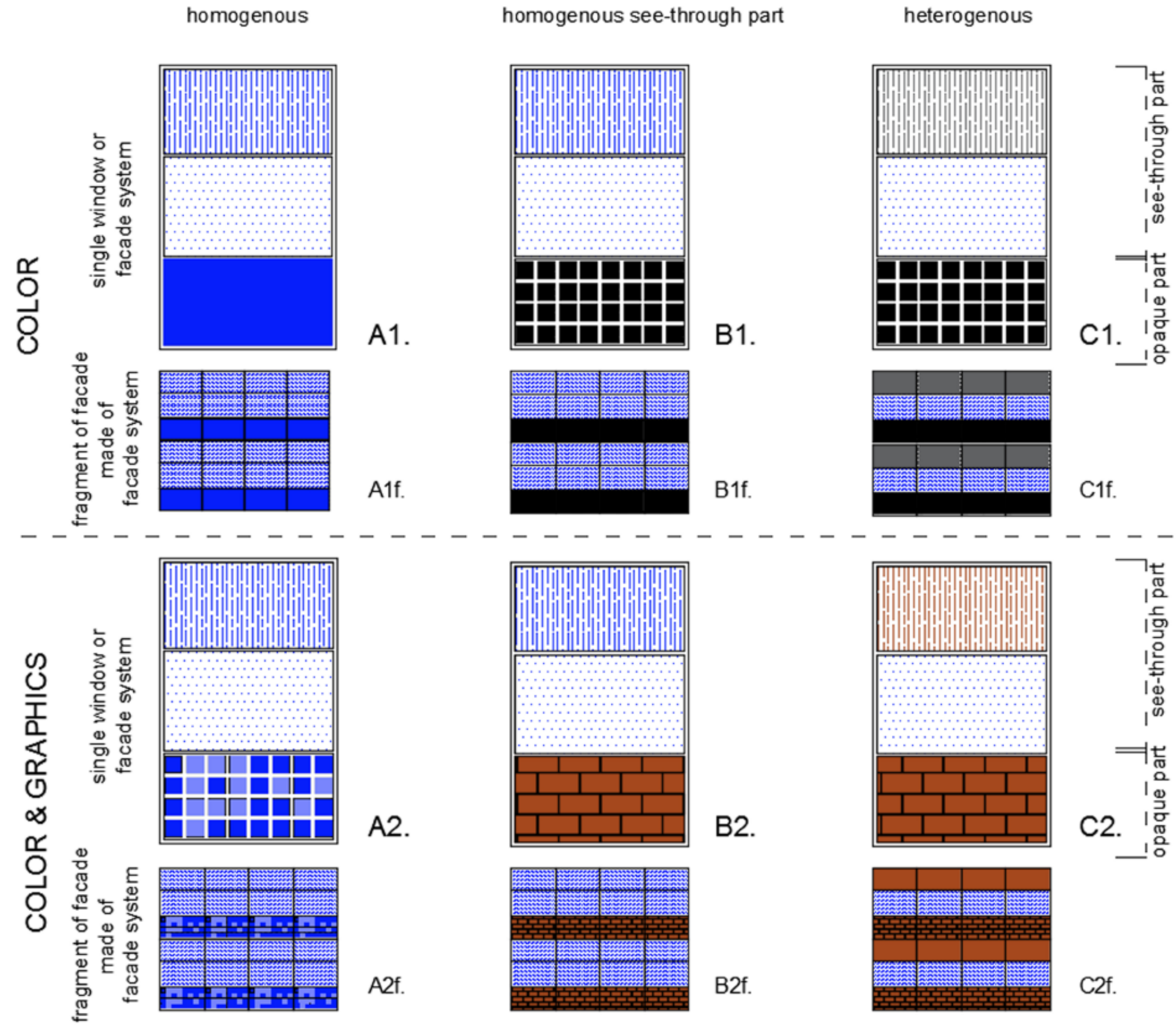

Figure 6.
Aesthetic potential of PV-EC SBS façade systems – an attempt at systematization based on 3-part window configuration (variant C/ Fig. 5) (by the author)

The proposed variants are exemplary and indicate the possibility of obtaining three basic aesthetic effects: homogeneous (A), contrasting (heterogeneous) (C) and indirect one, e.g., with a homogeneous appearance of the façade's see-through part (B) façade and within the window itself.

With regard to the façades, this results in the possibility of forming homogeneous all-glass surfaces (A1-2f), with the traditional drawing of windows (B1-2f), and ribbon windows (C1-2f), respectively.

The above possibilities, which provide an attempt to systematize the influence of the PV-SBS on the façade shaping in terms of its aesthetics, are presented in six configurations. In each case, the EC glazing takes up the middle strip of the window or the façade system:

Fig. A1: The upper strip: the PV module made of semi-transparent PV cells of the second-third generation in a color matching the EC glazing (second generation – the PV module coloring foils; third generation – the PV cell dye);

The bottom strip: PV module from first-third generation non-transparent PV cells with color matching to the EC glazing (second generation PV module of amorphous silicon non-transparent cells with coloring foil);

Fig. B1: as A1, the lower strip made of PV modules different in color from the EC glazing (in the drawing – monocrystalline silicon cells of the first generation in the natural color);

Fig. C1: as B1, with the upper strip made of translucent second or third generation cells in the natural color (amorphous silicon cells in the drawing);

Fig. A2: as A1, but the lower strip is made of PV modules made of first generation PV cells of different color obtained by applying a coloring foil onto their surface (in the figure, polycrystalline cells with a blue tinting foil: possibility to create inscriptions, graphics etc.);

Fig. B2: as B1, with the lower strip made of monocrystalline or amorphous non-transparent silicon PV modules with a coloring foil and graphic print (in the drawing - PV modules with a brick imitation print);

Fig. C2: as B2, the upper strip: PV module made of second-third generation translucent PV cells in a color matching the color of the bottom strip (second generation - coloring foils; third generation – cell dye).

6. SUMMARY

In the paper utility, energy and aesthetic analysis of the PV-EC technology has been discussed, which allowed for the assessment of these technologies from the architectural and construction point of view. Based on this assessment, theoretical window models were proposed as potentially adequate solutions for building applications of the PV-EC technology. These solutions constitute a bridge between the relatively extensive technological research on the PV-EC conducted worldwide and the architectural and construction perspective. The solutions translate the study into the design assumptions, as seen with account to the building users' needs. In this sense, the conducted research is pioneering. As contributory studies, they constitute the basis for further numerical and simulation research that require detailed, more individualized assumptions. These should mainly include:

- thermal and optical parameters of glazing (U, g, Tv, optical contrast);
- orientation and share of the façade glazing (glazing-to-wall ratio) in the room wall;
- characteristics of climatic conditions;
- room with the PV-EC window functional and spatial characteristics.

Given their theoretical nature, these research results can provide a general guide for architects while making their design decisions, especially at the initial design stages. At the present stage of technological development, however, the results serve mainly as an introduction to further research on improving the PV-EC properties towards the integration of the solution with the building and its architecture.

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