Challenges and Optimization of Building-Integrated Photovoltaics (BIPV) Windows: A Review

Shaohang Shi 1,2 and Ning Zhu 1,2,*

1 School of Architecture, Tsinghua University, Beijing 100080, China; shishaohang123@126.com
2 Key Laboratory of Eco Planning & Green Building, Ministry of Education, Tsinghua University, Beijing 100080, China
* Correspondence: 13717742900@163.com

Abstract: PV windows are seen as potential candidates for conventional windows. Improving the comprehensive performance of PV windows in terms of electrical, optical, and heat transfer has received increasing attention. This paper reviews the development of BIPV façade technologies and summarizes the related experimental and simulation studies. Based on the results of the literature research, the average comprehensive energy-saving rate of BIPV façades can reach 37.18%. Furthermore, limitations and optimization directions of photovoltaic integrated shading devices (PVSs), photovoltaic double-skin façades, and photovoltaic windows are presented. To improve the energy-saving potential of windows as non-energy efficiency elements of buildings, smart PV windows are proposed to be the key to breakthrough comprehensive performance. However, not all switchable windows concepts can be applied to PV windows. Typical studies on smart windows and PV windows are sorted out to summarize the challenges and optimization of smart PV window technical solutions. Considering the technological innovations in smart PV windows, two requirements of energy-saving materials and building envelopes are put forward. The advances in materials and the building envelope are complementary, which will promote the sophistication and promotion of solar building technology.

Keywords: building-integrated photovoltaics (BIPV); smart windows; switchable building façades; performance requirements; energy-saving materials

1. Introduction

With the progress of global warming and urbanization worldwide, experts in various fields have begun to pay close attention to the utilization of renewable energy [1]. The building sector accounts for more than 30% of total energy consumption [2], and it is essential to reduce energy consumption through renewable energy building technologies. The cost of maintaining indoor comfort is huge—HVAC energy consumption accounts for 50% of building energy consumption [3], and it is significant to reduce operational energy consumption through energy conversion and utilization approaches. Solar energy possesses the advantages of cleanliness, extensiveness, and continuity [4]. The development and promotion of solar building technology are imperative.

The building envelope, as a mediator between indoor and outdoor spaces, considerably impacting the level of building energy consumption [5]. The performance optimization design of a solar building envelope can effectively improve the efficiency of solar energy conversion and utilization. The typical solar building envelope can be divided into passive and active approaches. For passive solar building envelopes, whose energy-saving principles do not consume additional energy, they can respond spontaneously to solar radiation intensity, outdoor temperature, etc. Common approaches include wall-implanted thermal diodes [6], cooling coatings [7,8], sky radiation cooling materials [9], water-based windows [10], photochromic windows [11], thermochromic windows [12], windows integrated with PCMs [13], etc. Active solar building envelopes improve the building energy...
performance or enable building energy supply by consuming energy or converting solar energy. Typical technical solutions include terminal and envelope integration [14], insulated walls with pumped pipes [15], electrochromic windows [16], building-integrated photovoltaics (BIPV) roofs [17], etc. To improve buildings’ energy efficiency and indoor occupant comfort, many scholars have attempted to enhance the solar energy utilization efficiency of the building envelope.

Beginning with the first monocrystalline silicon cell with an efficiency of six percent developed at Bell Labs in 1954 [18], the development of photovoltaic technology has opened up various possibilities for people to exploit solar energy. Then, in the 1970s, people installed solar panels on the surface of buildings, enabling the off-grid operation of buildings in remote regions [19]. Building-integrated photovoltaics have been driven by technology and policy to evolve and become a widespread technical solution. This technology makes it possible to transform a building from an energy-consuming to an energy-producing facility. Typically, the roof of a building is exposed to more solar radiation than the building facade, and multiple stakeholders, such as owners, are more likely to favor BIPV on the roof of a building. In the context of promoting the concept of zero-energy buildings, the facade also serves as a non-negligible part of the application of BIPV technology. Especially for high-rise buildings, the area of the facade is much higher than that of the building roof, and adopting a BIPV facade has excellent potential [20]. In this paper, the challenges and optimization approaches for developing BIPV facade technology will be discussed and outlined, especially for switchable BIPV windows. This is because windows are considered to be one of the weakest building elements as there is always a heat transfer contrary to the occupants’ needs indoors [21]. Therefore, the optimal performance of BIPV windows is of great importance to improve the energy efficiency of buildings.

As shown in Figure 1, the research framework of this review is demonstrated. Section 1 introduces the research background of this paper. This section addresses the importance of popularizing solar technology and the current state of the solar building envelope development. In Section 2 below, the development of different BIPV facades is reviewed. BIPV facades consist of three main types: photovoltaic integrated shading devices (PVSDs), photovoltaic double-skin facades (PV-DSFs), and photovoltaic windows. At the same time, this section identifies the limitations encountered in the performance optimization of various BIPV facades in terms of “heat transfer, daylighting, and power generation”. It is also pointed out that switchable building envelopes are an opportunity to improve the performance of BIPV windows. Section 3 reviews the current state of smart window development and summarizes its features and limitations of combining with BIPV technology. Smart windows can be divided into two main categories, i.e., active smart windows and passive smart windows. In Section 4, the existing studies on smart BIPV windows are reviewed, and challenges and performance improvement approaches for BIPV windows are discussed. Finally, the direction of BIPV window development is prospected in Section 5. In the last section of this review, future paths for PV window performance improvement (material side and building envelope side) and criteria for its technology promotion and application are prospected. This study summarizes the performance limitations of existing PV windows and suggests that switchable PV windows are the key to improving energy efficiency. Finally, it points out the performance optimization path of PV windows from three levels: the material, building envelope, and technology application. The references included in this paper were obtained from Elsevier ScienceDirect, MDPI, SAGE Journals, and other literature databases. The keywords for the literature search include but are not limited to BIPV, PV window, smart window, building envelope, solar energy, renewable energy, etc.
2. Development of BIPV Façade Technologies

2.1. Energy Properties of Different BIPV Façades

Emerging innovative BIPV products provide numerous energy-efficient solutions for buildings (Figure 2). As shown in Figure 3, the basic principles of different BIPV façades are demonstrated: photovoltaic integrated shading devices (PVSDs), photovoltaic double-skin façades, and photovoltaic windows. They have different properties of power generation, heat transfer, and daylighting, respectively. For PVSDs, photovoltaic louvers as external shading can reduce indoor solar heat gain while generating electricity. For photovoltaic double-skin façades, switching between external circulation, internal circulation, and thermal insulation modes is possible depending on the heat transfer demands. Additionally, by enhancing natural convection within the cavity, it is possible to cool the PV modules, thereby increasing the power production of the PV system. Photovoltaic windows can be formed by replacing the glazing of the outer side of a double-glazed or multi-glazed glass with semi-transparent photovoltaic modules. PV windows can reduce passive indoor heat gain compared to conventional windows.
Figure 2. Application scenarios of different BIPV products: (a) opaque colored CdTe PV modules [22], (b) colored semi-transparent PV modules [23], (c) a photovoltaic double skin-façade [24], (d) photovoltaic integrated shading devices (PVSDs).

Figure 3. Cont.
Figure 3. Basic principles of three typical BIPV façades: (a) photovoltaic integrated shading devices (PVSDs), (b) photovoltaic double-skin façades, (c) PV windows.
2.2. Photovoltaic Integrated Shading Devices (PVSDs)

PVSDs combine PV panels as shading devices on building façades. Previous studies have explored the effects of various PVSDs with different design parameters on the building’s energy consumption. For static PVSDs, the angle of their PV panels is fixed and does not adjust with seasonal or personnel requirements. Mandalaki et al. [25,26] explored the variations in the performance of fixed PVSDs of 13 types on the building’s lighting, cooling, heating, and energy production with a simulation study of an office building. The differences in the calculation of energy production using different simulation methods were also compared. The results showed that the shading forms commonly used in office buildings (the horizontal louvers, outwards, or inwards inclined types) do not have the best performance in terms of energy savings. Therefore, the study pointed out that the retrofitting of building façades with renewable energy needs to focus on the effect of shading on comprehensive energy consumption. Zhang et al. [27] evaluated the energy-saving potential of single-panel photovoltaic shading based on “daylighting, heat gain and electricity generation” in Hong Kong. The variables involved in the study included the tilt angle and orientation of the PV panels. It was noted that there were differences in the parameter design of PV shading panels for maximum power generation and maximum energy-saving potential. Taveres-Cachat et al. [28] proposed a multi-objective optimization algorithm to improve the energy-saving potential of PVSDs, with optimized parameters including the number of photovoltaic louver modules, the angle at which the modules are tilted and the position on the vertical axis. The results show that energy savings of about 19 kW·h/m² can be achieved using the Pareto-optimal solutions. The method can provide a new collaborative starting point for various interest groups with different optimization objectives.

For dynamic PVSDs, whose external shading PV modules are varied, the stimulus for variation can be the indoor illuminance, the maximum energy production or the maximum shading effect. Nagy et al. [29–31] proposed a dynamic BIPV façade—a façade with angularly variable PV modules. The results showed that this variable BIPV façade can achieve 20~80% net energy savings compared to static PV shading devices and that the environmental impact of this dynamic BIPV façade is compressed based on a whole life cycle analysis that takes into account the dynamic energy savings.

When PVSDs are applied to multi-story buildings, the comprehensive energy-saving potential will change—this is because the PV shading modules on the higher floors will obscure the modules on the lower, which will change the PV power generation to a certain extent. Li et al. [32] developed the EnergyPlus simulation model to evaluate the comprehensive energy-saving potential and economic performance of applying PVSDs (the single panel type) in multi-story buildings, with variables including different tilt angles, different widths, and five typical climate zones. The results showed differences in the shading effect of PVSDs on higher floors vs on lower floors in different climate zones due to different latitudes. In addition, the study proposes a particular PV module that can reduce the effect of shading on the system performance. Shi et al. [33] explored the comprehensive energy-saving potential of applying different PVSDs in single-story and multi-story buildings and evaluated the impact of varying design parameters on the energy-saving potential. The results showed that for climate zones with low heating and cooling energy consumption, it is crucial to avoid PVSDs that reduce daylighting in the interior—the increased lighting energy consumption may account for a larger share of the total energy consumption. Furthermore, the study points out that the distance from the top edge of the window to the PV module is also a key parameter in the energy-efficient design of PVSDs.

2.3. Photovoltaic Double-Skin Façades (PV-DSFs)

BIPV double-skin façades can switch the convection heat transfer mode according to the outdoor environment or indoor occupants’ requirements, which can change the envelope’s performance in heat transfer, daylighting, or power generation. Yang et al. [34]
developed four photovoltaic double-skin façade energy models for the Australian climate by using the TRNSYS simulation tool to assess the impact of different design parameters on indoor thermal comfort. The study variables involved in the simulation process include PV glazing with different visible light transmittance, cavity thickness, and window U-value. The results showed that the cavity thickness should be fully considered for BIPV/T-DSF cases with fan ventilation, as this parameter has a notable impact on indoor thermal comfort. In addition, the study evaluated the effect of the window U-value on indoor thermal comfort. In another study by Yang et al. [35], the energy-saving potential of four photovoltaic double-skin façades was evaluated. The study included three PV materials: an a-Si PV, a dye-sensitized solar cell (DSSC), and perovskite solar cells. The study’s results showed that the building’s energy-saving rate could be up to 106% based on the parameters set in the study. Zhu et al. [36] proposed a double-skin façade based on concentrating PV modules and evaluated its heat transfer performance. Through the simulation results of TracePro 3.2 and Fluent 16.0 software, the study pointed out that the optimal channel width of this technology solution is 0.5 m, and the ventilation width is 0.2 m. The study also pointed out that the performance of this double-skin façade is superior to that of the conventional double-skin façade. Peng et al. [37,38] proposed a ventilation double-skin façade and explored the thermal and power generation performances under different convection regulations by experimental measurements. Moreover, in another study by Peng et al. [39], the EnergyPlus model was developed to evaluate the comprehensive energy performance of a BIPV double-skin façade. The analysis introduced variables such as air layer thickness and ventilation method. The results showed that, based on the technical parameters set up in the study, the minimum monthly net electricity consumption was only 2.6 kW·h/m². Combined with the comparative study analysis, it was found that the net electricity consumption of the proposed BIPV double-skin façades was only half that of conventional glazing.

Based on the above studies, it can be seen that BIPV double-skin façades with switchable performance based on forced convection heat transfer (e.g., mechanical ventilation) or natural convection heat transfer are of high flexibility. At the same time, choosing a rational airflow path is critical for the energy saving of a façade operation. At the same time, it is crucial to establish monitoring systems and mode-switching mechanisms—such as an air source decision program or an air velocity decision procedure [40].

2.4. Photovoltaic Windows

Many PV materials such as c-Si, CdTe, DSSC, and perovskite can be integrated into glazing. Different solar cells have distinct energy characteristics. He et al. [41] proposed an amorphous silicon photovoltaics window with a ventilated cavity. They investigated this window’s electrical and thermal properties based on a hot box experiment in the Hefei area. The results showed that this window can reduce the indoor radiative heat gain by 46.5% in summer. In addition, this double-glazed window can reduce the glass’s internal surface temperature, which will make the predicted mean vote (PMV) more desirable for indoor office occupants. Wang et al. [42] proposed a BIPV double-layer ventilated window based on CdTe solar cells, which enables seasonal regulation. This study explored the energy performance of the BIPV window. It evaluated the effect of the cavity thickness and PV coverage ratio on the energy-saving potential (thermal, optical, and PV production). The results showed that CdTe BIPV windows in this study can improve heat transfer performance in winter and summer and reduce building energy consumption. In addition, the increase in cavity thickness leads to a higher energy-saving potential of the envelope. In another study by Wang et al. [43], the optical performance and energy-saving potential of BIPV windows was investigated. The investigation of the light performance included experimental measurements of the actual spectral data and assessed the color quality of the transmitted light. It was shown that the practical BIPV window not only meets the seasonal thermal demand but also has a better color quality of the transmitted light. Lee et al. [44] applied a DSSV BIPV window in a building and carried out two years of energy
production monitoring. This PV material has the advantages of low cost and providing a colored aesthetic appearance (brownish red). The results showed that the PV windows in the experiments had power generation efficiencies ranging from 2.64% to 4.14%. Yu et al. [45] proposed a semi-transparent perovskite solar cell with an average of 10% to 30% visible light transmittance. It provides a new path for the application of BIPV windows.

Based on the above study, it can be seen that there is a trade-off between PV windows in terms of PV coverage (power generation capacity), daylighting, and heat gain. Typically, a more significant PV generation capacity results in a more miniature visible light transmission and a reduced solar heat gain. At the same time, more significant PV coverage also affects the view of indoor occupants. In addition, the quantitative characterization of daylighting performance in previous studies is dominated by illuminance. For PV cells of different materials, changes in the spectral distribution of solar energy through the PV window transmission occur [46], which need to be evaluated. The insight given by the above study is that PV windows with switchable convection heat transfer performance have a higher potential for energy savings. PV windows that can change their heat transfer performance according to different seasons or day and night energy demands will increase the envelope energy savings.

In addition, Table 1 summarizes the commercial status of PV windows and the corresponding case studies. Different PV glazes have different physical parameters regarding power generation, light harvesting, and heat transfer. Correspondingly, they differ regarding sight view, color rendering ability, comprehensive energy-saving effect, or aesthetics. By comparing the application scenarios of different PV modules, it can be seen that thin-film solar cells and 3D static solar concentrators have an advantage in cost. Thin-film solar cells consume less material, which results in lower prices. Three-dimensional static solar concentrators can utilize direct and diffused light throughout the day while only requiring a minor area of PV material. Therefore they have an advantage in terms of economic costs.

Table 1. A comparative discussion of the commercial status of PV windows.

<table>
<thead>
<tr>
<th>PV Window Types</th>
<th>Diagram</th>
<th>Economics and Performance Aspects of the Application Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparent CdTe PV glazing</td>
<td></td>
<td>PV coverage rates requiring parametric design optimization, especially in different climate zones where the potential for energy savings needs to be evaluated before application; less material consumption and lower cost</td>
</tr>
<tr>
<td>[43]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-transparent perovskite PV modules [45]</td>
<td></td>
<td>Available with different visible light transmittances; transmitted light color quality evaluations required</td>
</tr>
</tbody>
</table>
### Table 1. Cont.

<table>
<thead>
<tr>
<th>PV Window Types</th>
<th>Diagram</th>
<th>Economics and Performance Aspects of the Application Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spaced type PV glazing [47]</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td>PV cells possibly affect the visibility of people indoors</td>
</tr>
<tr>
<td>See-through a-Si PV glazing [48]</td>
<td><img src="image2.png" alt="Diagram" /></td>
<td>Light transmission design optimization is necessary; transmitted light color quality evaluations are required</td>
</tr>
<tr>
<td>Luminescent solar concentrator (LSC) [49]</td>
<td><img src="image3.png" alt="Diagram" /></td>
<td>Collection of both diffuse and direct light; transmitted light color quality evaluations required</td>
</tr>
<tr>
<td>Semi-transparent organic PV glazing (OPV) [50]</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td>Available in designed colors; low production costs; already available in both flexible and rigid applications; long-term stability as the key to its commercial expansion</td>
</tr>
<tr>
<td>Three-dimensional static solar concentrator [51]</td>
<td><img src="image5.png" alt="Diagram" /></td>
<td>Direct and diffused light can be utilized throughout the day; lower costs (smaller area of PV materials)</td>
</tr>
<tr>
<td>Thermochromic halide perovskite solar cells [52]</td>
<td><img src="image6.png" alt="Diagram" /></td>
<td>The transmittance of modules varies at different temperatures, which has the effect of preventing overheating; color change temperature requiring design; transmitted light color quality evaluations required</td>
</tr>
</tbody>
</table>

### 2.5. Summary: Limitations and Solutions of BIPV Façades

In summary, it can be seen that the research on PVSDs, PV-DSFs, and PV windows involves three key areas: electrical, heat transfer, and optical. For façades with semi-transparent PV modules, the critical research areas of the technology also involve colorimetry (e.g., evaluation of the color quality of the transmitted light). In terms of energy performance, the former three critical areas mentioned above are mainly concerned with the...
energy consumption of the building during the operation period (to maintain a comfortable light, thermal, and humidity-controlled indoor environment). The comprehensive energy consumption ($E_{\text{COM}}$) of a building with BIPV façades examines four types of building energy consumption, which are heating energy consumption ($E_H$), cooling energy consumption ($E_C$), lighting energy consumption ($E_L$), and PV generation ($E_{PV}$). The sum of the former three may often be called total energy consumption ($E_{\text{TOTA}L}$). The calculation of the total energy consumption and the comprehensive energy consumption is shown below:

$$E_{\text{TOTA}L} = E_H + E_C + E_L$$  \hspace{1cm} (1)

$$E_{\text{COM}} = E_H + E_C + E_L + E_{PV}$$  \hspace{1cm} (2)

The comprehensive energy saving ratios ($\text{SR}_E$) of a building are usually compared with the total energy consumption of the building of the base case ($E_{\text{BASE}}$). It should be noted that the base case here usually refers to a case that does not utilize any BIPV façades. The comprehensive energy-saving rate is calculated as shown below:

$$\text{SR}_E = (E_{\text{COM}} - E_{\text{BASE}})/E_{\text{BASE}}$$  \hspace{1cm} (3)

As shown in Figure 4, a comparison of the comprehensive energy-saving ratios of three types of BIPV façade is demonstrated. The period of the quantitative data for the energy savings assessment is the whole year in typical climate zones to sufficiently assess the energy savings of different BIPV façades in all seasons. At the same time, the applicability of BIPV façades in various climate zones was also evaluated. The range of latitude values contains 12.4~51°, covering both southern and northern latitudes. The energy savings in the different cases are up to 106%, achieving the near-zero energy consumption goal. For different BIPV façade technologies, the average value of comprehensive energy savings is 37.18%. More than one-third of the energy savings can be realized. The data in Figure 4 come from previous publications, and the data and charts are summarised by abstracting the building energy consumption data. It can be found that the advantages of the comprehensive energy-saving effect of different BIPV translucent building envelopes are reflected in the fact that the envelopes can produce energy so that the electricity generated by the envelopes can be used for the energy consumption by terminals, such as heating, cooling or lighting—their energy-saving effect is better than that of the solely passive building envelopes.

Nevertheless, for building envelopes such as photovoltaic windows or static PVSDs, the thermophysical parameters of the envelope are not switchable. This means that their energy savings are not necessarily superior to conventional non-capacity building envelopes in areas that are in extreme heat or cold throughout the year. As an example, Roberts et al. [53] and Jhumka et al. [54] indicate that the application of BIPV façades in London (51° N) and Mauritius (20° S) may result in an increase in energy consumption in the range of 1.66% to 8.00%. In other words, for extremely hot climate zones, PV glazing with a large PV coverage ratio can lead to less heat gain and more power generation. However, PV windows of this parameter type may substantially increase the energy consumption of indoor artificial lighting, potentially leading to an increase in the net energy consumption of the building. For extreme cold climate zones, PV glazing is possible to introduce a certain amount of electrical energy for building energy consumption. However, PV glazing, even with lower PV coverage ratios, reduces the heat gain of the building interior during the day and increases the indoor artificial lighting energy consumption. Not only that, but cold regions are also likely to have issues with high PV panel temperatures, especially in the middle of the day on sunny days. Whether or not the PV panels need to dissipate heat, as well as variations in indoor heat exhaustion/gain demand, set a challenge for the energy efficiency of static BIPV façades. Therefore, a comparison of the performance differences between switchable and static BIPV façades is presented. As shown in Table 2, different BIPV façades solutions with switchable convection heat transfer or other switchable performance have greater potential for energy savings and are applicable to a wider range of climate
zones. Envelopes with switchable performance can meet the building’s energy efficiency needs in different seasons, for example, when ambient outdoor air can be used as a natural cooling or heating carrier, or when solar radiation is not required to bring heat gain to the interior. Moreover, the switchable BIPV façade allows for a proper breakthrough in the mutual containment between the PV coverage ratio and the optical/thermal performance of the building envelope.

Figure 4. Comparison of annual energy saving ratios of three BIPV façades in different locations at different latitudes [33,35,39,48,53–57].

BIPV double-skin façades’ energy-saving effect is highly related to the promptness of regulation, so their control logic determines the effectiveness of the energy-saving of the building envelope. The regulation and decision-making mechanisms of double-skin façades become particularly complex in the face of transitional seasons or sudden changes in meteorological conditions. For PVSDs, the shading of the lower PVSDs by the higher floors in a multi-story building can result in a restriction of the benefit generated per unit area of invested PV panels—a significant cost for BIPV products that is closely related to the number of PV panels used [58]. Therefore, there are certain limitations on the employment of PVSDs. In addition, due to the significant advantage of shading panels in reducing radiative heat gain [59], applying shading components in cold regions may result in increased cold loads. Thus, their applicability to a full range of climate zones must be evaluated carefully.
Table 2. Comparison of different BIPV façades’ performance in the previous literature.

<table>
<thead>
<tr>
<th>Facade Types</th>
<th>Refs.</th>
<th>Year</th>
<th>PV Materials</th>
<th>Variable Performance</th>
<th>Energy-Saving Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surrounding shading PVSDs have the maximum power generation, and brise soleil semifaçade louvers PVSDs have the minimum power generation; the more PV panel area used does not necessarily mean that more power is generated</td>
</tr>
<tr>
<td>Mandalaki et al. [25,26]</td>
<td>2012, 2014</td>
<td>Monocrystalline silicon</td>
<td>-</td>
<td></td>
<td>In the case of Hong Kong, the southern elevation is best tilted at 30° to maximize power generation, and the southern elevation is best tilted at 20° to maximize the potential for comprehensive energy-saving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>With the Pareto-optimal solution, energy savings of approximately 19 kW·h/m² can be realized</td>
</tr>
<tr>
<td>Zhang et al. [27]</td>
<td>2017</td>
<td>Polycrystalline silicon</td>
<td>-</td>
<td></td>
<td>A 20–80% net energy saving compared to static PV shading devices</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The optimal tilt angles for installing PVSDs in Harbin, Beijing, Changsha, Kunming, and Guangzhou are 55°, 50°, 40°, 40°, and 30°, respectively, and the optimal PV panel width is 1.156 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The average comprehensive energy savings of different PVSDs ranged from 16.12% to 51.95%</td>
</tr>
<tr>
<td>Facade Types</td>
<td>Refs.</td>
<td>Year</td>
<td>PV Materials</td>
<td>Variable Performance</td>
<td>Energy-Saving Effects</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------------------------</td>
<td>------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>----------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>BIPV double-skin façades</td>
<td>Yang et al. [34,35]</td>
<td>2019, 2020</td>
<td>Amorphous silicon PV, dye-sensitized solar cell (DSSC), and perovskite solar cells</td>
<td>Heat convection</td>
<td>Building energy savings of up to 106% based on the set parameters in the study</td>
</tr>
<tr>
<td></td>
<td>Zhu et al. [36]</td>
<td>2020</td>
<td>GaAs</td>
<td>Heat convection</td>
<td>The comprehensive heat transfer coefficient is 1.179 W/(m²·K) with an exhaust heat of 143.70 W</td>
</tr>
<tr>
<td></td>
<td>Peng et al. [37,38]</td>
<td>2013, 2015</td>
<td>Amorphous silicon</td>
<td>Heat convection</td>
<td>Ventilated BIPV façades can reduce indoor heat gain and increase power generation by 3%</td>
</tr>
<tr>
<td></td>
<td>Peng et al. [39]</td>
<td>2016</td>
<td>Amorphous silicon</td>
<td>Heat convection</td>
<td>Electricity production of 65 kW·h per unit area per year; net electricity consumption can be reduced by about 50%</td>
</tr>
<tr>
<td></td>
<td>He et al. [41]</td>
<td>2011</td>
<td>Amorphous silicon</td>
<td>Heat convection</td>
<td>46.5% reduction in indoor radiant heat gain in summer; lower inner glass surface temperature</td>
</tr>
<tr>
<td>BIPV windows</td>
<td>Wang et al. [42]</td>
<td>2021</td>
<td>CdTe</td>
<td>Heat convection</td>
<td>Seasonal regulation; heat transfer energy savings of 205.76 kW·h and 333.09 kW·h in winter and summer, respectively</td>
</tr>
<tr>
<td></td>
<td>Wang et al. [43]</td>
<td>2022</td>
<td>CdTe</td>
<td>Heat convection</td>
<td>Winter and summer window SHGCs are 0.28 and 0.11, respectively</td>
</tr>
<tr>
<td></td>
<td>Lee et al. [44]</td>
<td>2018</td>
<td>Dye-sensitized solar cell (DSSC)</td>
<td>-</td>
<td>Photovoltaic window power generation efficiency of 2.64–4.14%</td>
</tr>
<tr>
<td></td>
<td>Yu et al. [45]</td>
<td>2020</td>
<td>Perovskite</td>
<td>-</td>
<td>A power conversion efficiency of 16.7%; average visible light transmittance of 10–30%</td>
</tr>
</tbody>
</table>

Windows are essential elements for every building, but they are considered one of the weakest envelope components because there is always a heat transfer against people’s expectations [21]. The optimal design of window performance is relevant to the energy efficiency goals of buildings in all climate zones. For BIPV windows, the collaborative optimization of their optical, heat transfer, and power generation capabilities has the potential for exploitation. The shift from a static envelope to a performance switchable
building envelope for PV windows can satisfy a broader range of application scenarios. By integrating the outer glass layer of smart windows with PV glazing, switchable thermo-physical parameters and power generation performance are formed, i.e., BIPV smart windows [60].

3. Smart Window for Energy Savings

This section presents an overview of smart window technology to evaluate window technologies suitable for incorporating PV glazing. The technological solutions are classified as active and passive smart windows according to whether their operation consumes energy.

3.1. Active Smart Windows

Typical active switchable windows include electrochromic windows, windows with flowing liquid (pump-powered), etc. Electrochromic windows achieve a reversible transformation of parameters such as the visible light transmittance of windows by consuming a certain amount of electrical energy. They can also reach the purpose of privacy protection according to the requirements of occupants. To assess the energy-saving potential of electrochromic windows, Xu et al. [61] proposed a multi-objective energy-saving optimal design method based on electrochromic windows, taking a classroom as an example. The results showed that the total annual energy consumption could be reduced by 254 kW·h, and the percentage of optimized time for the indoor illuminance level was improved by 65.4%. The regulation of electrochromic windows requires an intelligent control system or manual adjustment by workforce. Still, it does not have the advantage of a spontaneous response to air temperature and solar radiation intensity. To improve the automatic adjustment advantage of the window, Zhang et al. [62] proposed a window that combines electrochromic and thermochromic functions by using thermochromic cellulose hydrogel as an electrolyte. This window has a personalized utilization mode. In addition, water-based windows formed by injecting water into the windows can improve the disadvantage of the low heat capacity of the windows and increase solar energy utilization. For example, a prototype and numerical modeling of a multifunctional recirculating dynamic water-based window technology was reported in a study by Li et al. [63], which evaluated the energy-saving potential of windows filled with water with different absorption rates. Such windows can reduce air-conditioning energy consumption and use up to 21.25% to 28.76% of projected solar energy. Applying energy storage materials such as phase change materials in water-based windows can further improve the performance of energy-saving devices in buildings, e.g., Yamaç et al. [64] developed a solar thermal energy storage system by combining the concepts of phase change materials and water flow windows. The energy consumption of the cooling system of this technology solution can be compressed to less than 85% and stores 2916 kJ of energy in six hours.

3.2. Passive Smart Windows

According to the different modes of heat transfer, passive smart windows mainly include radiation-regulated smart windows and heat-conduction-regulated smart windows. According to the different sources of stimulation for the discoloration of different smart windows, passive smart windows include photochromic windows, thermochromic windows, etc. The irradiation of ultraviolet rays stimulates the discoloration of photochromic windows. Nicoletti et al. [11] discussed the energy and visual performance of photochromic windows through experiments and simulations that found photochromic windows effective in preventing glare. The EnergyPlus modeling based on the climate zone of southern Italy revealed that annual energy savings for photochromic windows could be between 4.1% and 9.3%. The temperature of the glazing stimulates the discoloration of thermochromic windows, and thermosensitive materials such as VO₂, hydrogels, ionic liquids, liquid crystals and perovskites [65] are commonly employed. Aburas et al. [12] proposed a thermochromic window based on VO₂ nanoparticles, which can achieve energy savings ranging from 7.1
to 46.4% per year. It is worth mentioning that the transition temperature \cite{66} of the thermochromic coating applied in the window needs to be evaluated to achieve a parametric design with optimal energy savings.

From the point of view of energy decoupling and utilization, the solar energy band is primarily concentrated in the range of 250–2500 nm \cite{67}, containing a large proportion of visible and near-infrared (NIR) energy, and a small amount of ultraviolet (UV) band energy. Taking the needs of windows in buildings in summer or hot regions as an example, it is crucial to maximize the transmission of visible light but minimize the transmission of near-infrared light. Smart windows that decouple light and heat transfer are one of the solutions for these scenarios. Responding to this need, Zhang et al. \cite{68} proposed a flip-flop window using ATO nanofluid to fulfill different window energy performance needs in winter and summer. Based on the results of winter experiments, this technological solution was shown to delay the appearance of peak indoor temperatures, and it could improve the level of indoor thermal comfort at night.

When energy-efficient windows are operated for a considerable time, dust may accumulate on surfaces, reducing the amount of indoor solar radiation transmission—which is particularly unfavorable for energy efficiency in buildings in cold regions. To deal with this problem, Zheng et al. \cite{69} provided a multifunctional membrane solution that simultaneously achieves energy efficiency, self-cleaning and anti-fogging functions. However, it is worth mentioning that this coating used on the outer surface of the building envelope may be affected by phenomena such as ultraviolet rays from solar radiation and rainwater erosion. This type of functional material’s durability and cyclic stability \cite{70} need to be evaluated.

For passive smart windows dominated by heat transfer regulation, adding water, liquid gels, or phase change materials to the window cavity can improve its thermal mass. Priya et al. \cite{71} proposed a translucent window filled with liquid gel and explored its benefits in terms of reduced heat gain, net operating costs, and CO$_2$ emissions. Variables involved in the study included different glass cavity thicknesses (4 mm, 8 mm, and 12 mm), and a comparison was also carried out with conventional double glazing. This window solution showed an excellent color quality of transmitted light, uniformity of daylighting, and a short economic payback period (4.97 to 6.16 years). Window phase change materials can effectively reduce peak indoor temperatures and improve indoor thermal comfort at night due to their excellent latent heat storage capacity. For example, a PCM window filled with paraffin wax with a melting temperature of 35°C is proposed by Goia et al. \cite{13}. This window can reduce energy gain by more than 50% in summer and indoor heat loss in winter. As for the optimal design of the parameters of the phase change window, Li et al. \cite{72–74} conducted a series of studies on the phase change material modification research and development of the phase change window, characterization of window component performance and outdoor experimental testing. The analysis was carried out to optimize the design of the phase change window with parameters such as the mediator thickness of the phase change window and the phase change temperature. It should be noted that the phase change material may affect people’s visual effect before melting, so the design and application of phase change windows ought to be combined with the indoor operating temperature and climate conditions of buildings.

### 3.3. Combining Smart Windows with PV Glazing: A Discussion

Based on the above literature review, it can be concluded that the application of active smart windows has high operation and maintenance costs. It is essential to avoid the scenario in which the energy consumed by the system to control the window changes is greater than the energy saved by switchable windows. As for passive smart windows, the regulation process does not consume additional energy and has the advantage of being spontaneous. According to the principle of regulation, passive smart windows mainly include reversible windows, wavelength-selective transmission windows, color-changing windows, phase-change windows, etc. In addition, according to whether or not the variable
material is adopted, smart windows can be divided into two categories: static smart windows and dynamic smart windows. Static windows are usually used in cold or hot regions, i.e., they have a clear tendency to demand heating or cooling energy. Dynamic windows are used in climatic zones with a combination of summer and winter, and can be seasonally adjusted. By combining smart windows with PV glazing, the energy-saving effect is realized by the fact that the PV-covered part of the window generates electricity used for the building’s operating energy consumption. The light-transmitting portion of the smart PV window is adjustable for optical and thermal performance, realizing flexible energy savings.

Taking the thermochromic PV window as an example, this paper develops a building performance simulation model based on EnergyPlus. The building is located in Guangzhou, with a length and width of 6000 mm and 8000 mm, respectively, and a building height of 3900 mm (Figure 5a). The building has one window on the south façade, equipped with three technological parameters: a conventional window, a thermochromic window and a thermochromic photovoltaic window. For building envelopes with variable transmittance, such as thermochromic windows, the visible light transmittance ($T_{\text{lum}}$) and solar transmittance ($T_{\text{sol}}$) at different temperatures affect their ability to regulate light and heat. $T_{\text{lum}}$ refers to the transmittance of the visible wavelengths of the solar spectrum through the glazing. It is calculated using the following formula:

$$T_{\text{lum}} = \frac{\int_{380}^{780} \varphi_{\text{lum}}(\lambda) T(\lambda) d\lambda}{\int_{380}^{780} \varphi_{\text{lum}}(\lambda) d\lambda} \quad (4)$$

$T_{\text{sol}}$ refers to the transmittance of the solar spectrum through glazing. It is calculated using the following formula:

$$T_{\text{sol}} = \frac{\int_{250}^{2500} \varphi_{\text{sol}}(\lambda) T(\lambda) d\lambda}{\int_{250}^{2500} \varphi_{\text{sol}}(\lambda) d\lambda} \quad (5)$$

The spectral properties of the thermochromic glazing at different temperatures are shown in Figure 5b, which is derived from EnergyPlus 8. The building performance comparison is evaluated regarding the comprehensive energy-saving ratio. The results show that compared to the base case, the building in Guangzhou can achieve an energy-saving ratio of 2.6% by using thermochromic windows. After replacing the thermochromic glass on the exterior surface of the building envelope with thermochromic PV glazing (PV coverage of 19.20%), the energy-saving rate increases to 12.61% (Figure 5c).
4. BIPV Smart Windows

4.1. BIPV Smart Windows Reported in the Previous Literature

4.1.1. Radiation-Regulated Switchable PV Windows

Semi-transparent PV modules usually have a fixed visible light transmittance. Combining photochromic, thermochromic or electrochromic glazing with a PV module can form a PV smart window, breaking through the trade-offs between production capacity, optics and heat transfer performance [75]. Malara et al. [76] proposed an electrochromic PV window device that could rapidly switch the visible transmittance. The study evaluated the effect of different catalytic areas on the module’s performance. The results showed that the larger the catalytic size of the module, the higher the conversion efficiency. Huaulmé et al. [77] proposed a photochromic DSSC cell with variable color phase and transmittance of the module with a power generation efficiency of 4.17%. The results showed that the visible light transmittance of this photochromic cell module was reversibly transformable from 27% to 59% with a stability of more than 50 days. A series of studies by Wu et al. [78–81] reported a technological solution for thermochromic films in smart PV windows. The development process of this novel thermochromic photovoltaic window included thermochromic film development, experimental tests on specimens, and numerical simulations, and its energy-saving potential was demonstrated. The color-changing film applied in the window can effectively respond to the exterior environment and work without the advantage of manual maintenance. Nie et al. [82] proposed a switchable PV component combining fluorescent dyes and thermochromic materials, which can achieve a dynamic response to solar radiation and temperature, and effectively improve the photoelectric conversion efficiency. Lin et al. [52] proposed a perovskite window component that combines energy production and thermochromism. This device’s peak photoelectric conversion efficiency was higher than 7%, and the visible light transmittance ranged from 35.4% to 81.7%. Although this semi-transparent color-changing device has a memory temperature of 105 °C, it provides a reference for developing new types of windows. To solve the problem of matching the discoloration temperature of perovskite materials with the energy-saving needs of buildings, Liu et al. [83] proposed a perovskite-based thermochromic photovoltaic device, a technological solution that had good optical regulation and a low discoloration temperature (29.4–51.4 °C). When the semi-transparent cell was warmed up, it turned into a dark reddish–brown, so the spectral shape of its transmitted light was questionable. Gotz-Kohler et al. [84] proposed a gasochromic PV window that allowed the user to switch its visible light transmittance according to needs, such as energy saving or privacy. The composition of the photovoltaic cell employed a semi-transparent germanium solar cell and a gasochromic switchable magnesium mirror in a glass cavity. The study’s results showed that this technological solution could generate more than 20 kW h/m² per year.

The above studies discussed state-of-the-art solutions to change the solar transmittance of PV windows through thin films or gas layers with variable transmittance. In recent years, sky radiation cooling technology has been developing rapidly [85], and using semi-transparent cooling films in PV windows can reduce the cooling load of buildings. Tang et al. [86] proposed a window that generates electricity during the daytime and utilizes sky radiant cooling during the nighttime and carried out the performance tests and the development of a MATLAB-based simulation program. The results show that this switchable PV window can reduce the energy demand in the cooling season by 208.16 MJ/m² compared to the traditional transparent glass window. This window also provides a new perspective on the application of sky radiative cooling technology—sky radiative cooling has notable advantages such as all-weather, low cost, etc., and its use in locations such as skylights can reduce the cooling demand of buildings in hot regions. Another benefit is that the thermal management of PV panels using sky radiant cooling materials can maintain sufficient electrical efficiency of the PV system due to temperature coefficients [87]. It is critical to note that the application of sky radiative cooling technology in translucent building envelopes requires the design and fabrication of metamaterials in conjunction with specific building scenarios, taking into account the need for the creation...
of the building’s indoor environment (thermal comfort for occupants, improving crop yields [88], etc.) and the climate characteristics (precipitation throughout the year, cloud cover, etc.). Like thermochromic glazing regulating solar transmittance, the energy-saving potential of sky radiative cooling windows with switchable emissivity [89] is considerable.

Generally, metal ions in the film of a semi-transparent PV module may change the color quality of the transmitted light, and the PV coverage may result in a loss of visible light. A PV glazing material that selectively transmits solar energy in the visible band and converts or reflects energy in the UV and near-infrared bands to generate electricity would be an ideal PV glazing material, as it would break the bottleneck of the game between electrical, optical, and thermal properties of PV glazing. Facing this problem, Liu et al. [90] proposed a halide perovskite PV cell with a high transmittance of visible light, which selectively utilizes UV light for the power generation process. The results showed that the color rendering index (Ra) of the transmitted light of this component was higher than 93. This study provides insights and references for the material design of future novel batteries.

4.1.2. Thermal Conduction-Regulated Switchable PV Windows

The radiation-regulated PV smart windows explored in the previous section do not have significant changes in the window U-value before and after coloration, and building envelopes with dynamic thermal conductivity regulation performance can reduce building loads when outdoor air temperature and humidity are under unfavorable conditions [91]. For example, PV windows filled with phase change materials in the glass cavity can achieve dynamic thermal conductivity and radiation composite regulation of the envelope. As the temperature of the PV window rises from a low temperature past the phase change temperature of the phase change material, the phase change material also absorbs the waste heat from the PV window to keep the PV cell with a sufficient amount of electrical efficiency.

Elarga et al. [92–94] investigated the electrical and thermal performance of a three-glass, two-cavity PCM-PV window by discussing its energy-saving potential through simulation calculations. The results showed that 60% of cooling energy could be saved by applying this energy-efficient window technology in Venice and 36% of heating energy could be saved by applying this energy-efficient window technology in Helsinki. Ke et al. [95] compared the difference in electric and thermal performances of the hollow PCM-PV windows and conventional PV windows through simulation calculations. The results showed that based on the climate of Hefei City, the new PV window can provide an improvement in production capacity, indoor thermal comfort and a reduction in indoor air-conditioning energy consumption by 1246.87 kW·h.

4.2. Challenges

4.2.1. Energy Conversion Efficiency and Temperature Coefficient of PV Materials

For PV products, having a higher solar conversion efficiency, excellent durability, and shorter economic payback cycles are more likely to be favored by homeowners, which is the main reason why silicon-based solar cells have the largest market share [96]. Although many materials have high conversion efficiencies, their material durability and power stability for outdoor applications need to be assessed. The reason is that novel materials may fail under rain and snow erosion, high temperatures or prolonged outdoor exposure. Differences in the wavelength bands utilized by different PV materials, i.e., they respond differently to the solar spectrum, are critical for optimizing the performance of BIPV windows. Utilizing more of the UV or near-infrared bands for power generation and maintaining a higher visible light transmission would be the ideal thin-film PV material for windows.

Different PV materials also have various temperature coefficients and larger temperature coefficients lead to more energy loss. From Figure 6, it can be seen that the temperature coefficients of different PV materials are distributed between $-0.21\sim-0.72%/^{\circ}\text{C}$. Conventional BIPV systems rely on passive cooling techniques such as cooling with the help of
natural outdoor convection, but this only applies if the outdoor air can be used as a cooling source. If forced convection, such as mechanical ventilation, is employed to cool the PV panels, additional energy consumption may occur—the electrical gain from maintaining a stable production capacity needs to be weighed against the electrical power consumption of mechanical ventilation. On the contrary, passive thermal management materials or waste heat utilization materials that do not consume additional energy, such as radiative cooling from the sky or phase change materials, make sense in combination with PV systems. In the case of phase change materials, for example, when selecting thermal management materials, attention needs to be paid to the optimal design of parameters such as the phase change temperature, enthalpy of phase change, thickness, etc. Otherwise, it may result in the temperature of the BIPV window not passing through the phase change temperature, leaving the phase change material inactive. Another advantage of using phase change materials in combination with PV modules is that the residual heat of the phase change materials after sunset will make the BIPV envelope temperature decrease slowly, but at this time there is no solar radiation, so it does not affect the power generation efficiency.

![Figure 6. Comparison of temperature coefficients of different PV materials [48,97–101].](image)

**Figure 6.** Comparison of temperature coefficients of different PV materials [48,97–101].

### 4.2.2. Building Façades Receive Little Solar Radiation

For windows on the façade, they receive less solar radiation compared to the roof. To cope with this issue, PV windows can be placed at an angle towards the sky during the daytime of the transitional season in the form of external opening windows (Figure 7). However, attention should be paid to the fact that the upper-story PV window may block the amount of solar radiation projected from the surface of the lower-story PV panels when opened. Attention should also be paid to the shading of the façade by buildings or trees in the surrounding environment [102], which can be avoided by morphological design or location in the early stages of the program to evade the capacity loss caused by this problem.
4.2.3. Suitable Building Energy-Saving Scenarios

Different seasons and climate zones have different energy requirements for PV windows, and smart PV windows can be used to compensate for the inability of static envelopes to meet changing outdoor parameters or the dynamic needs of occupants indoors. Therefore, the development of metamaterials makes sense for improving the performance of translucent building envelopes—which will reduce the undesired energy transfer. At the same time, metamaterials can help to break through the electrical, optical, and thermal game of the light-transmitting BIPV envelope and achieve the performance goal of “1 + 1 > 2”. For example, for hot regions, excessive solar energy transmission into the interior through windows is not expected. Thermochromic windows can reduce the indoor cooling load in times of overheating. If PV windows and thermochromic windows are coupled, the excessive solar energy can be converted into electricity and the passive benefits of PV layers can be used to reduce indoor heat gain. In this scenario, the union of PV windows technology and smart windows technology is a co-benefit. For the material side, the challenge lies in how to prepare materials with appropriate technological parameters, such as the color change temperature of thermochromic materials, the selective radiation transmittance or reflectance of semi-transparent materials, and the enthalpy of phase change of materials. For smart BIPV windows, the utilization or regulation of the near-infrared wavelengths in solar energy puts demands on the materials field.

4.2.4. Color Quality of Transmitted Light

The color quality of transmitted light from poorly designed windows affects people’s light comfort [103], thermal comfort [104], work performance and mood [105], etc. The reported studies have paid more attention to the visible light transmittance and illuminance effect on indoor desktop height when evaluating the optical performance of novel BIPV windows. However, for energy-efficient windows, the spectral distribution of transmitted light should also be evaluated [106]. Relevant physical indicators include correlated color temperature and color rendering performance. This possibility should be especially noted for thermochromic PV windows that change color phase after warming. As shown in Figure 2b, the appearance of a blue semi-transparent PV module is demonstrated. Shi et al. [23] explored the color rendering index of the transmitted light of this module under sunny conditions in Beijing. The color rendering index contains 15 standard colors. \( \Delta E_i \) characterizes the color difference between the color coordinates of a color sample illuminated by a light source to be evaluated and a reference light source. The formula for \( \Delta E_i \) is as follows:

\[
R_i = 100 - 4.6\Delta E_i
\]
The color rendering index is calculated from the arithmetic mean of eight low-saturation standard colors $R_i$ with the following formula:

$$R_d = \frac{1}{8} \sum_{i=1}^{8} R_i$$

As shown in Figure 8 the CRIs of the transmitted light of the blue semi-transparent PV glazing are distributed between $-52$ (R9) and 88 (R14). The color rendering index of the transmitted light is 64, a value that falls into the “Unreasonable” category [103]. The data suggest that the application of colored semi-transparent PV modules in buildings may affect the indoor visible light spectral distribution.

![Figure 8](image-url)

**Figure 8.** The CRIs for the transmitted illuminant of the blue semi-transparent PV module (data derived from reference [23]).

Furthermore, from a materials chemistry point of view, when fabricating novel semi-transparent PV modules, attention should be paid to the type and valence of the metal ions in the material, as this may change the shape of the transmitted light spectrum. For example, the proportion of Fe ions in glass with different valences [107] can make the glass appear yellow or blue–green. Changing the proportion of Ti ions of different valences in the glass will make the glass appear yellow [108].

### 4.2.5. Robustness of Novel PV Modules

The robustness of novel PV modules requires attention as the building envelope is affected by solar radiation, natural outdoor convection, air temperature, and humidity, and the energy production principle of the PV module requires that it be located on the outer-most side. It is important to note that the laboratory power does not necessarily mean that the outdoor application will have the same energy efficiency. For BIPV smart windows, if metamaterials are used, freeze–thaw cycles, color fading cycles and hysteresis during temperature changes need to be taken into account to avoid material degradation at low temperatures during rain and snow or at high temperatures during the summer months when the solar radiation is extremely intense. This should be evaluated in advance when applied to glass to avoid expansion and cracking of the glass due to the volume change. In addition, the loss of power generation due to dust, bird droppings and other foreign substances deposited on the surface of PV modules [109] needs to be ensured such that solar conversion efficiency is maintained by timely cleaning.

### 4.2.6. Economics

From the production process point of view, thin-film solar cell production costs are low [110]—the semiconductor film is attached to the back layer and consumes much less semiconductor material than traditional silicon cells. However, from a material perspective,
while some novel cells consume very little material and have large power generation efficiencies (e.g., GaAs cells with energy efficiencies of up to 27.5% [111]), their production costs are high, so the potential for widespread application is limited. In addition, if some high-cost metal elements are utilized in the fabrication of PV modules, the cost will also increase.

4.2.7. Effects of Application in Full-Scale Buildings

Most of the existing studies reported are device studies of PV smart windows, i.e., the studies are mainly focused on small-scale laboratory experiments. The effect of PV devices employed in full-scale buildings is unknown, and full-scale buildings should be built in the future to verify the energy-saving potential of BIPV smart windows. Particular attention should be paid to the impact of windows on the indoor environment of the building, and the relevant technological indicators include desktop illuminance, correlated color temperature, the color rendering performance [112], the temperature of the inner surface of the glass, the air temperature [113] and the sound-blocking performance [114].

4.3. Optimization

4.3.1. Materials

- Photovoltaic materials

  The promotion of the solar energy conversion efficiency of PV materials can directly increase the amount of energy produced by PV products. In addition, there are differences in the response of different PV materials to solar energy wavelengths [115]. Therefore, PV modules used in PV windows will be more suitable if they can utilize the near-infrared and ultraviolet wavelengths to generate electricity—such modules will not interfere with the transmission of visible light through the window into the room, allowing for the decoupling of the use of light and heat. Different PV materials also have different temperature coefficients—the lower the temperature coefficient is, the easier it is to ensure sufficient PV efficiency, which is especially critical in hot climates, so this can be used as a reference for material design.

- Optical/thermal regulation materials

  For all productive and non-productive smart windows, optical and thermal performance is an issue that must be addressed in all window technology solutions. Therefore, the development of semi-transparent thermal management materials can provide a basis for the development and performance improvement of PV smart windows. Relevant technology strategies include the use of sky radiative cooling materials to reduce the surface temperature of the PV layer [116], the employment of thermochromic materials to meet the seasonal needs of buildings [117] and the reduction in the external surface temperature of PV windows through phase change materials [118]. It is worth mentioning that thermochromic materials will have great potential for energy saving if they can achieve the switchable modulation capability in both solar and atmospheric window wavelengths at the same time [119].

  In the manufacturing of semi-transparent thin-film photovoltaic modules, attention should also be paid to the choice and combination of chemical elements. This is because metal ions in specific valence states may change the indoor-side transmission spectral distribution, resulting in a reduction in the color quality of the transmitted light, thus altering the indoor color temperature as well as the color rendition of indoor objects. For example, Kondrashov et al. [120] investigated the effect of different substance percentages of iron ions, CoO and Se co-doped glazing on the color of glass, and showed that the glass would exhibit green–sky-blue, sky-blue, gray, bronze, dark bronze or amber colors.

  In addition to optimizing the material design of the envelope itself, the selection of suitable functional materials to be applied to the surface of BIPV modules can also improve the energy performance of the building. For example, self-cleaning coatings with high transmittance and low reflectivity applied to the surface of PV windows can prevent
dust accumulation, thus reducing incident solar losses and guaranteeing module power generation. Common self-cleaning coatings include TiO2 hydrophilic or SiO2 hydrophobic layers [121,122].

4.3.2. Building Envelopes

- From static to switchable building envelopes

Conventional ways of optimizing the performance of the building envelope include increasing the thickness of thermal insulation [123], adopting shading devices [124] and applying multiple layers of glazing [125]. However, these static envelope techniques may suffer from problems such as large space consumption and cannot meet the energy demand of buildings in different seasons. For example, in the transitional season, outdoor air imported by window ventilation can be a source of indoor cooling or heating, which serves the purpose of saving air-conditioning energy consumption. In addition, there are also different thermal performance objectives for the envelope in terms of heat rejection or heat preservation to cope with the energy-saving objectives in winter or summer. Therefore, the energy-saving potential of the switchable building envelope is more significant, as it can respond to the dynamic needs of the occupants or changes in physical parameters outdoors to achieve flexible energy-saving goals [126].

In addition to the previously mentioned technology solutions for translucent building envelopes with switchable performance, for opaque envelopes, the building energy-saving potential can be enhanced by variable convection, heat conduction, or radiant heat transfer performance. As an example of a building envelope with switchable convection, Formentini et al. [127] proposed a shape memory metal-based ventilation switchable envelope, where the deformation process is driven by the phase transition of a metal wire. In summer, the metal panels are heated to an open state, which enhances the natural convection in the cavity and achieves heat removal from the enclosure. In winter, the panels are in a closed state, with less air convection in the cavity and less heat loss from the building. As an example of a thermal conduction switchable building envelope, Boreyko et al. [128] explored a planar form of a thermal diode roof, where water droplets jumped on a superhydrophilic surface to achieve unidirectional heat transfer. During the heat gain of the envelope, the droplets carry away heat from the superhydrophilic surface while the condensed droplets jump back to the evaporative side. As an example of a switchable envelope for radiative heat transfer, Tang et al. [129] proposed a sky radiation cooling material that can respond to different environmental temperatures, and the coating has adjustable emissivity at different temperatures. When the material is used in the building envelope, different temperatures exhibit different radiative heat transfer capabilities. When the material temperature is below 22 °C, the envelope is in solar heating or insulation mode. When the material temperature is increased to above 22 °C, its atmospheric window emissivity will increase from 0.20 to 0.90, allowing for sky radiation cooling.

- A discussion on achieving performance optimization of PV windows

Dynamic PV windows are recognized for their flexible energy efficiency, which makes them more energy-efficient compared to static PV windows. At the same time, PV windows can generate electricity to supplement building energy consumption. It is important to note that the combination of a performance-switchable building envelope and PV window technologies needs to focus on the application scenarios, as the combination of the two technology solutions may not necessarily achieve the energy-saving effect of “1 + 1 > 2”. For example, there may be trade-offs between energy consumption and production capacity, or thermal regulation materials lead to higher temperatures on the outside surface of the PV window (causing a reduction in power generation efficiency).

If PV windows are combined with active switchable building envelope technology, it is important to be mindful of the possible electrical energy consumption of pumps, electrochromic layers, etc. For specific climate zones, the electricity consumed for envelope switches is going to result in greater energy savings. In addition, active switchable building
envelopes should also pay attention to intelligent control methods that respond to dynamic demands through environmental monitoring [130]. If passive switchable technology is used, then attention should be paid to the design of the transformation conditions of the physical properties of PV windows. As in the case of photochromic windows, this technological solution may bring negative benefits in winter, as the UV rays from sunlight are present all year round and will stimulate discoloration in all seasons. This process can lead to an increase in heating energy consumption in winter, which is not beneficial for the building energy efficiency throughout the year. For thermochromic glass, attention should be paid to the setting of the memory temperature, as well as the changes in transmittance and reflectance of the glass before and after the discoloration [131]. Attention should also be paid to the transition gradient widths [132], as these determine the rate at which the discolored glass responds accordingly to the temperature parameters, which in turn affects the heat transfer performance of the light-transmitting envelope. For phase change materials, attention should be paid to thermophysical parameters such as the density, melting temperature and enthalpy of phase change of the work mass. In particular, for gas–liquid phase change materials, physical property parameters such as latent heat of vaporization and kinetic viscosity are also required [133]. However, as previously described, the application of dynamic thermal management materials should try to avoid an excessive temperature increase on the outer surface of the PV window, which can lead to the loss of power generation of the PV module.

5. Outlook

This paper provides an overview of the different technology solutions for BIPV façades, including PVSDs, BIPV double-skin facades, and PV windows. Based on the statistics of 173 comprehensive energy-saving ratio data, the energy-saving efficiency of various BIPV façades reaches 37.18%. Next, the weakness of BIPV windows as a building element is addressed, pointing to the performance switchable building envelope as an important opportunity to improve the energy efficiency of PV windows. Further, a literature review was conducted on smart windows, exploring the possibility of combining smart window and PV window technologies. This is followed by an extensive discussion of the development of BIPV smart windows. Remarkable progress has been made in the field of materials and building physics in the study of PV smart windows, but they are still facing challenges and optimization in their distance from building applications:

- **From the material point of view**, the development of new PV materials and optical/thermal regulation materials is an important contribution to the optimization of the energy-saving performance of PV windows. However, the development of new ideal PV window materials should have smaller temperature coefficients, lower costs, higher robustness and no significant change in the color quality of the transmitted light into the interior (avoiding unreasonable color rendering indexes for transmitted light, i.e., $R_a \leq 80$).

- **From the perspective of the building envelope**, the application of PV windows needs to focus on the comprehensive energy-saving scenarios to be achieved by the building. There are differences in daylighting, heat transfer, and power generation differences between buildings in various climate zones, seasons and hours of the day and night. PV smart windows that satisfy the switchable scenarios of insulation and heat gain have more potential for energy saving. A passive switchable building envelope does not require a control strategy and has the advantage of an automatic response. Active switchable envelopes are more capable of regulation but may be characterized by system complexity or additional energy consumption. In addition, PV windows of façades may have the limitation of receiving less radiation, which can be increased by tilting the window when ventilating, which thus increases the PV production capacity.

- **From the perspective of building applications**, short-term or long-term experimental research on full-scale smart PV windows should be carried out in the future. The actual energy-saving effects of theoretical studies need to be verified by long-term data moni-
toring, and the assessment of indoor people’s acceptance should be introduced [134]. It is since some new models of windows, although they have good energy-saving potential, may affect the sight of windows or the subjective acceptance of people.

In summary, this paper provides an overview of the challenges and methods for optimizing the performance of PV windows. With the emergence of new technologies in the field of materials and building envelopes, BIPV envelopes will be developed and popularized. The discussion and outlook of this paper provide a reference for the research and application of BIPV windows, aiming to promote the advancement of solar technology.

**Author Contributions:** Conceptualization, S.S.; formal analysis, S.S.; funding acquisition, N.Z.; investigation, S.S.; methodology, S.S.; supervision, N.Z.; visualization, S.S.; writing—original draft, S.S.; writing—review and editing, S.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by National Natural Science Foundation of China (Project No. 51978358).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


64. Yang, R.J.; Skandalos, N.; Karamanis, D. A Multi-Objective Optimization Method Based on an Adaptive Meta-Model for Classroom Design with Smart Electrochromic Windows. Energy 2022, 243, 122777. [CrossRef]


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.