



REVIEW

Optical, Thermal, and Electrical Properties of Building-Integrated Photovoltaics (BIPV): A Critical Review

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ABSTRACT: Building-integrated photovoltaics (BIPV) has attracted growing attention due to its promising applications in modern buildings. By serving as components of the building envelope, BIPV avoid competing with land use and facilitates net-zero energy buildings in the face of the current energy crisis. In addition to power generation, BIPV alters the energy-related properties of buildings. Appropriate daylighting and effective management of heat gains can reduce lighting, cooling, and heating loads, helping to balance energy production and consumption. This review examines the optical, thermal, and electrical behaviors of BIPV systems and their impacts on building energy efficiency. The discussion of optical properties emphasizes the visible spectrum, solar PV response spectrum, and atmospheric window. Thermal considerations focus primarily on BIPV/thermal (BIPV/T) systems and on the regulation of solar heat gain coefficient (SHGC) and U-value. Electrical performance is analyzed with respect to cell coverage ratio, window-to-wall ratio (WWR), and shading effects. Finally, key barriers to widespread BIPV deployment are identified, including challenges in architectural integration, cost-effectiveness, and aesthetic design. This work aims to provide a useful reference for researchers and practitioners engaged in BIPV design.

KEYWORDS: Solar energy; building-integrated photovoltaics; energy saving; building energy consumption

1 Introduction

Solar photovoltaic (PV) technology, as a leading renewable-energy solution, has strong potential to mitigate the energy crisis and advance sustainability [1]. Ongoing technological progress has driven rapid PV deployment, with installed capacity expected to exceed 30 terawatts by mid-21st century [2]. However, in regions where land is scarce, large ground-mounted PV arrays create land-use conflicts [3]. Building-attached photovoltaics (BAPV) and building-integrated photovoltaics (BIPV) extend PV applications by combining PV with buildings, thereby avoiding competition for land and facilitating net-zero energy buildings [4]. Furthermore, they also enhance the resilience of building power resilience through on-site power generation, especially for regions where power outages are common or come with a high cost [5]. Although the mixture of BAPV and BIPV is probably the best solution, BIPV might be the only option for high-rises due to the limited roof area.

The BIPV concept emerged in the 1990s as an approach to transform PV modules from add-on power system into alternatives to conventional building materials [6]. As illustrated in Fig. 1, PV modules can be

integrated into many parts of the building envelope, including roofs [7,8], façades [9,10], windows [11,12], and external sunshades [13,14]. Beyond electricity generation, BIPV elements must satisfy essential building performance requirements such as daylight transmission, thermal insulation, structural strength, watertightness and fire safety [15,16].

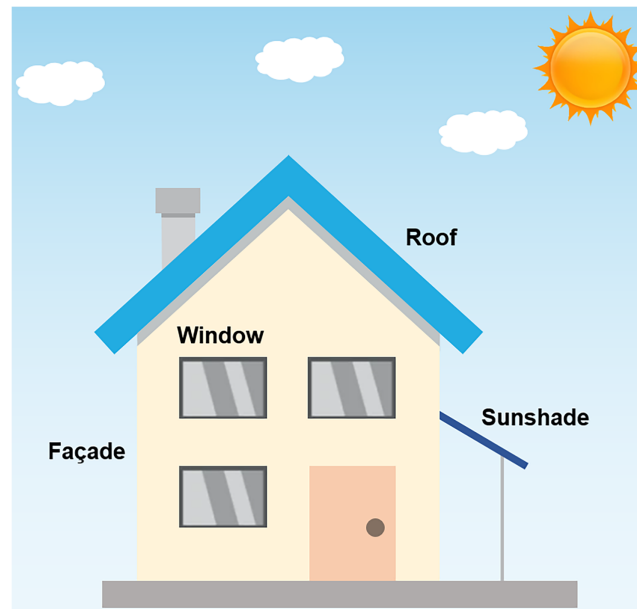


Figure 1: Schematic of various BIPV application categories.

As a significant standard, IEA PVPS Task 15 provides valuable reference for evaluating the electrical performance of BIPV systems [17]. However, it does not fully address the additional functional and safety demands that arise when PV becomes part of the building envelope. In recent years, International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), and relevant European technical committees have developed standards and technical guidance addressing BIPV safety, durability, electrical efficiency, aesthetics, and structural/functional integrity [18–22]. For BIPV systems in different climates or for different building types, it is necessary to further refine the application guidelines to maximize the overall benefits. Given that buildings account for roughly 30%–40% of global final energy consumption [23], attention to BIPV daylighting and solar heat gains has grown, promoting numerous case studies of BIPV optical, thermal, and electrical behaviors [24].

Requirements for BIPV vary with the envelope element and application. Most studies concentrate on a specific BIPV configuration and its characteristic energy performance, and a comprehensive synthesis of optical, thermal, and electrical behaviors across BIPV types is lacking. Therefore, this review surveys the energy-related properties of different BIPV systems and analyzes how these properties influence building energy performance. Specifically, in Section 2, the optical properties including visible light transmission, solar absorption relevant to PV response, and mid-infrared emission within the atmospheric window are examined. Section 3 involves thermal behaviors, focusing on the utilization and management of additional solar thermal energy and the consequent effects on building energy use. Section 4 analyzes three key factors (cell coverage ratio, window-to-wall ratio, and shading effect) affecting electrical performance, considering not only energy generation but also the potential for reducing building energy consumption.

2 Optical Properties

Early BIPV installations favored opaque roof systems because roofs do not require transparency and offer strong solar capture potential [25]. The wider deployment of semi-transparent photovoltaic (STPV) technologies has enabled PV integration into glazing, giving BIPV elements daylighting capability and extending their use to transparent building envelopes [26]. Beyond visible transmittance, optical behavior across the solar spectrum ($0.3\text{--}2.5\ \mu\text{m}$) and the mid-infrared atmospheric window ($8\text{--}13\ \mu\text{m}$) has become increasingly important because it is to some extent related to the thermal and electrical performance of BIPV systems. This section summarizes the basic principles briefly.

2.1 Transmission of Visible Light

Daylighting strongly influences indoor visual comfort and building energy use [27]. Sufficient natural light reduces reliance on electric lighting, lowering energy consumption while creating a comfortable and healthy indoor environment. The window-to-wall ratio (WWR) and the average visible transmittance (AVT) of the glazing are two primary factors affecting the indoor lighting levels, as shown in Fig. 2 [28]. Current BIPV glazing products cover a wide AVT range (approximately 20%–80%), making them viable substitutes for traditional glass in many applications [29]. In BIPV windows, visible light is typically transmitted through gaps between encapsulated opaque PV cells, which creates an intrinsic trade-off between power conversion efficiency (PCE) and daylighting performance [30].

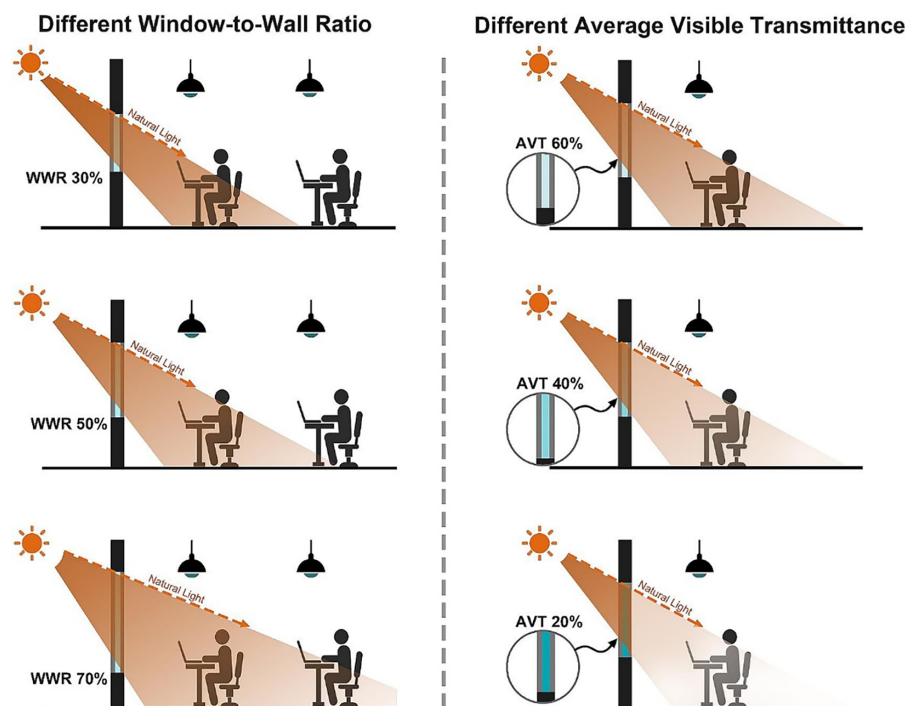


Figure 2: Indoor daylighting of BIPV windows with different WWRs and AVTs [28].

Most STPV modules are based on crystalline silicon or thin-film technologies (amorphous silicon, CdTe, and CIGS) [31]. Peng et al. [32] produced a novel BIPV laminate by slicing mono-crystalline silicon cells into narrow strips and evaluated daylighting performance of the resulting insulated glass unit (IGU), as shown in Fig. 3. Compared to a reference glazing, the BIPV IGU exhibited lower discomfort glare owing to its reduced visible transmittance. For the test room with a size of 6 m by 9 m, the daily lighting

energy consumption increased by 166 Wh, while daily power generation rose by 1985 Wh, indicating substantial energy-saving potential. Liu et al. [33] examined the effects of PV etching ratio and cavity depth in a double-skin façade employing CdTe STPV modules, as presented in Fig. 4. Annual simulations across different climates showed that lower etching ratios are preferable in summer, whereas higher etching ratios are beneficial in winter. Etching ratios of 30%–50% are generally appropriate for most cities. A smaller cavity depth improves daylight penetration and reduces lighting energy consumption, but excessively shallow cavities can cause overheating. They reported that a cavity depth of approximately 0.2 m was recommended to balance daylighting and thermal risk. Recently, Yu et al. [34] developed a semi-transparent organic photovoltaic (ST-OPV) window, which achieves a balance between light utilization and aesthetic transparency (Fig. 5). The light utilization efficiency of the fabricated solar cells can reach 6.05%, with a highly transparent aesthetic reddish hue closely approaching the AM1.5 G coordinates.

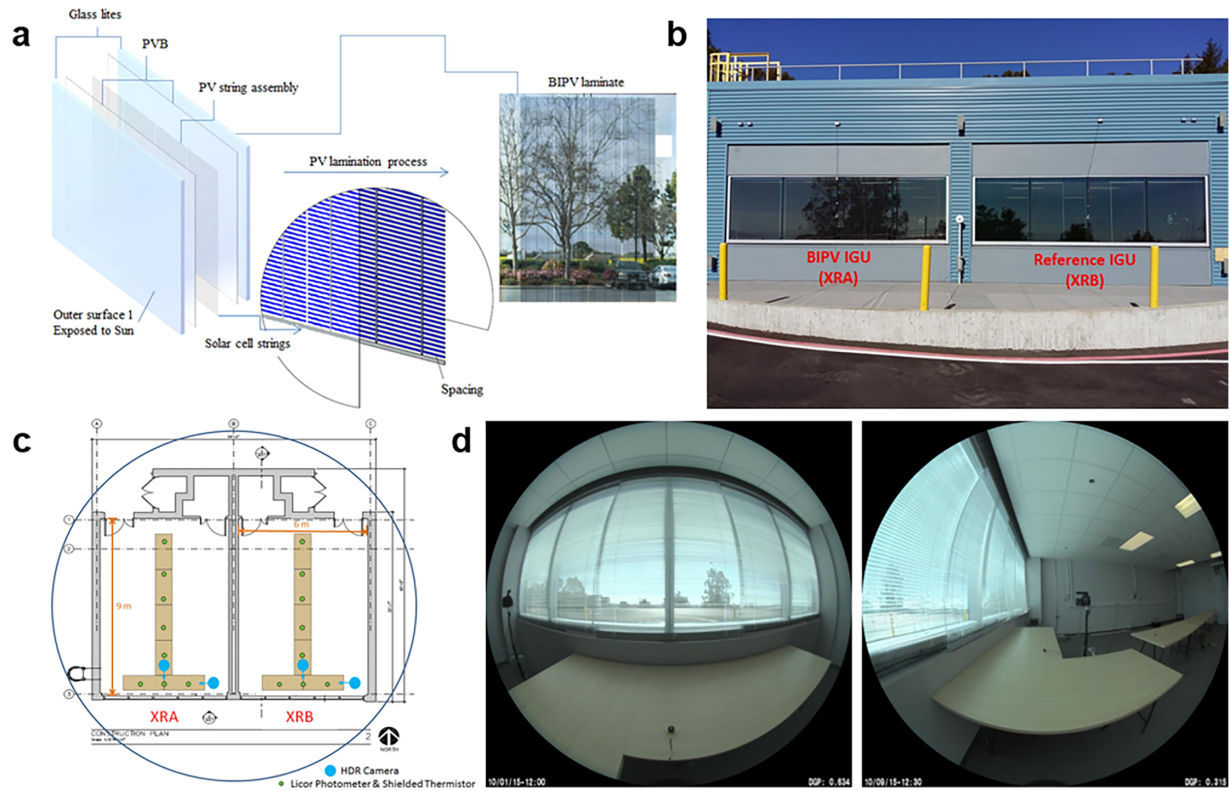


Figure 3: (a) Construction diagram of BIPV laminate; (b) photograph of the BIPV IGU and reference IGU; (c) layout of sensors in the BIPV and reference test rooms; (d) fisheye views from seated height looking toward (left) and parallel (right) to the window [32].

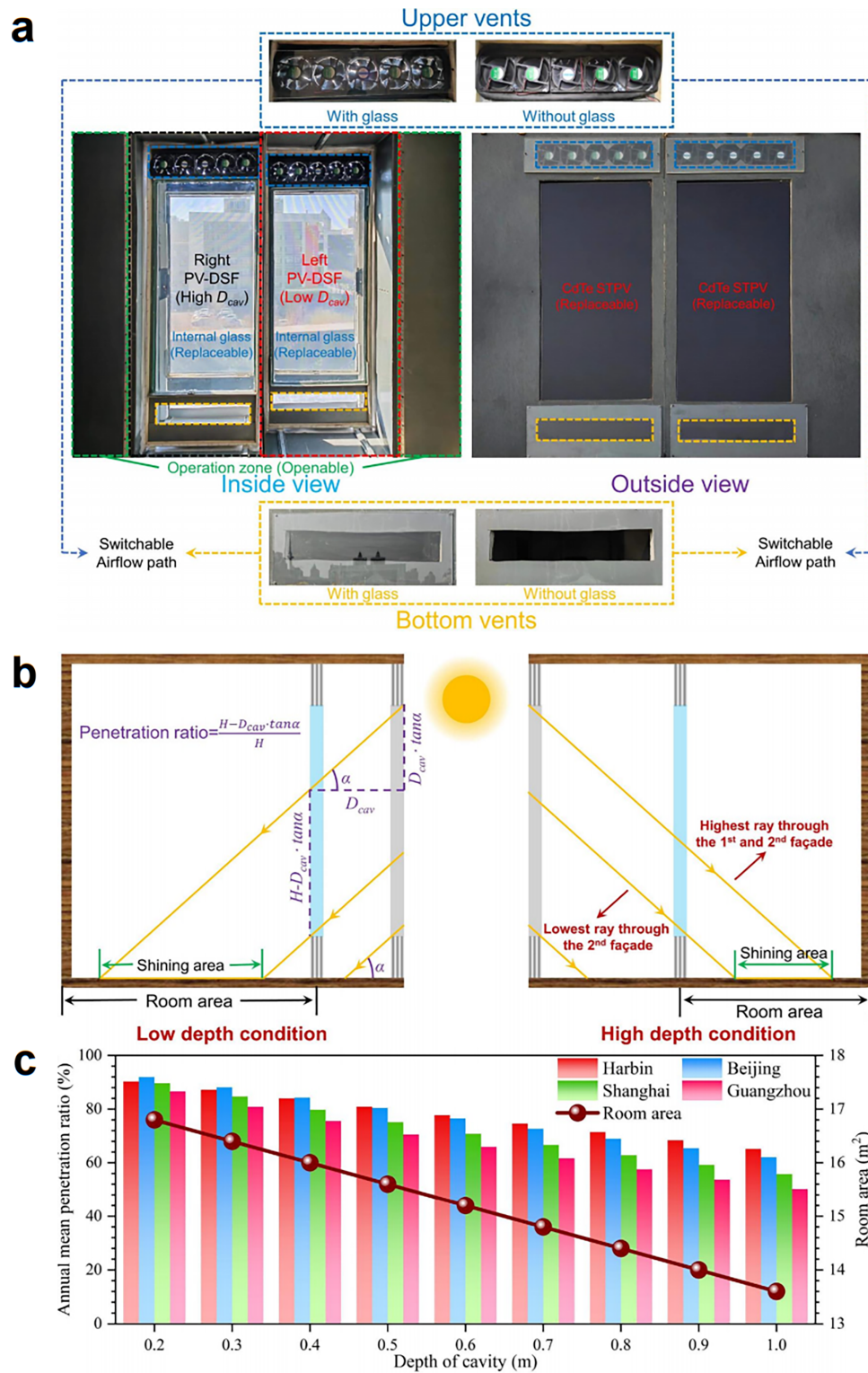


Figure 4: (a) Photograph of the experiment rig; (b) diagram of room area and shining area for low and high cavity depth conditions; (c) annual mean penetration ratio and room area with different cavity depth [33].

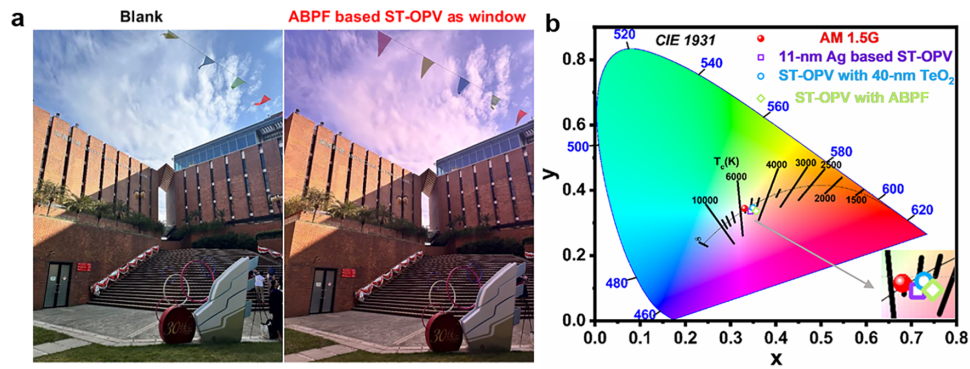


Figure 5: (a) Photographs of blank and aperiodic band-pass filter (ABPF) based ST-OPV window; (b) CIE1931 coordinates of corresponding ST-OPV window [34].

2.2 Absorption of Solar Radiation

Maximizing absorption in the wavelength range that overlaps the PV response is a direct and effective route to improve PCE for all BIPV modules. A common strategy is to modify surface optics to reduce reflection loss and enhance light trapping. Zhu et al. [35] proposed a V-shaped micro-lens light trapping structure for CIGS cells used in BIPV (Fig. 6). In façade applications, a geometry with a 60° vertex angle and 200 µm groove depth produced the best performance, increasing captured irradiance by 7.63% within the visible spectrum and 6.91% within the near-infrared compared with conventional configurations for roof and sunshade scenes. The variation of the external quantum efficiency (EQE) of common PV materials with respect to wavelength helps better understand the significance of spectral regulation in enhancing the PCE [36]. Besides, due to the change in solar position, the solar incident angle varies diurnally and seasonally. When the incident angle exceeds the Brewster's angle, reflection losses can rise sharply, significantly degrading the absorption of sunlight in most cases [37]. Mechanical sun-tracking can mitigate this effect but incurs extra energy use and system complexity. Passive wide-angle anti-reflection solutions are therefore attractive. For example, as shown in Fig. 7, Lee et al. [38] fabricated a hierarchically patterned film on ST-OPV cells that produces optical asymmetry. Specifically, the reflection depends on the direction of incidence. Bifacial application of these hierarchical films maximized light trapping and increased current density by about 13.5% under AM 1.5G illumination.

2.3 Emission within the Atmospheric Window

The concept of radiative cooling has motivated efforts to increase envelope emissivity within the atmospheric window to enable passive cooling. High-emissivity coatings and spectral-selective layers are commonly applied to building surfaces to promote thermal emission to the sky [39]. When this technology is introduced into BIPV, it is necessary to ensure the radiative cooling surface is in direct contact with the building rather than being separated from it, such as BIPV/T systems that will be mentioned later. Otherwise, the benefits of radiative cooling for the building would be almost negligible. Moreover, designs must balance strong absorption of solar radiation with enhanced mid-infrared emission, since the PV surface must still harvest sunlight efficiently. As shown in Fig. 8, Zhao et al. [40] placed a spectrally selective layer on the top of crystalline silicon cells that combines high absorptance (emissivity) within the PV conversion spectrum and the atmospheric window. Their design yielded total electricity generation plus cooling energy gains nearly double (~96.96% higher) those of a conventional BIPV module. Façade-mounted BIPV face additional challenges because large oblique view angles towards the sky reduce effective radiative cooling [41]. To address this, Kim et al. [42] developed a micropism sheet with polyethylene terephthalate (PET) for BIPV

façades (Fig. 9). It provides broadband, omnidirectional anti-reflection and, when integrated with glass, achieves emissivity close to unity across the atmospheric window. Such solutions can substantially improve the radiative cooling potential of façade PV while maintaining good solar harvesting.

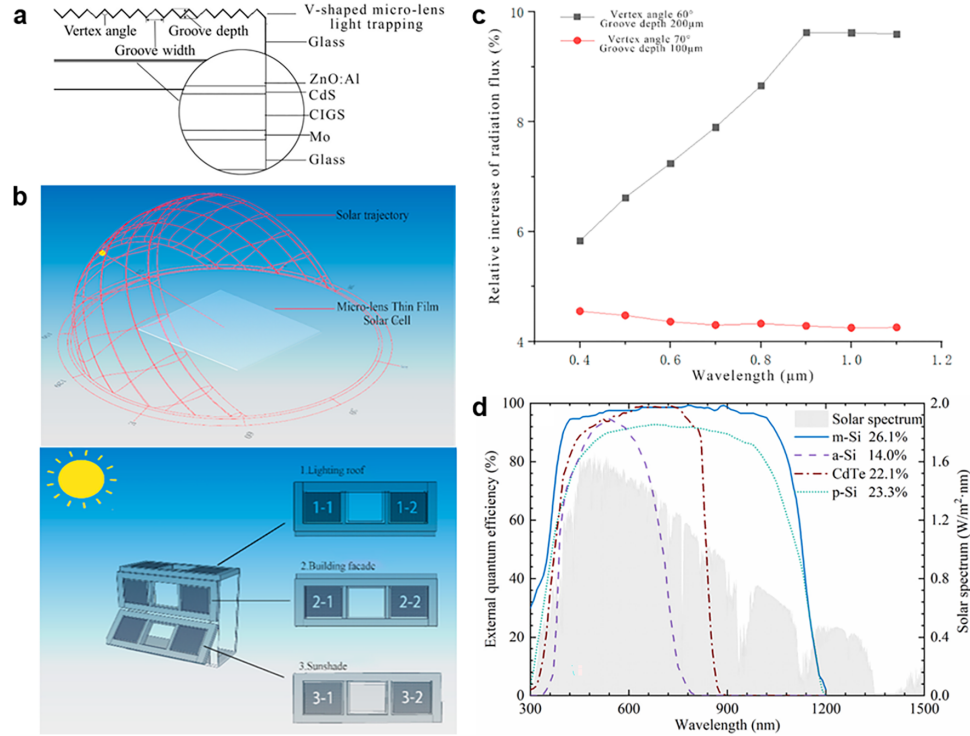


Figure 6: (a) Diagram of CIGS solar cell with V-shaped micro-lens light trapping structure; (b) schematic diagram of optical simulation in three BIPV scenes (top: simulation layout; bottom: three BIPV scenes including roof, façade, and sunshade); (c) relative enhancement of radiation flux of the CIGS solar cell absorption layer incident surface [35]; (d) EQE of common PV materials (m-Si: monocrystalline silicon; p-Si: polycrystalline silicon; a-Si: amorphous silicon) [36].

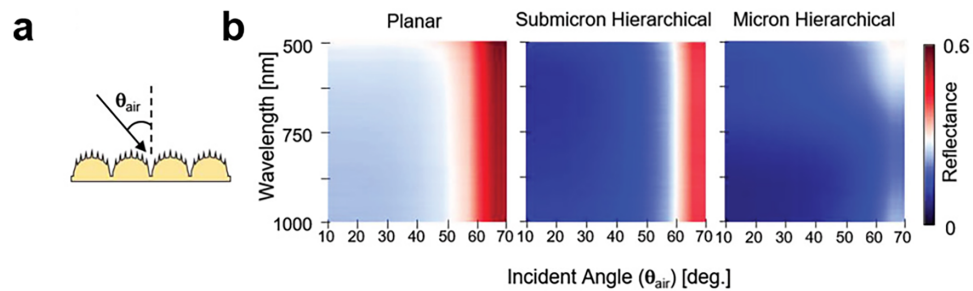


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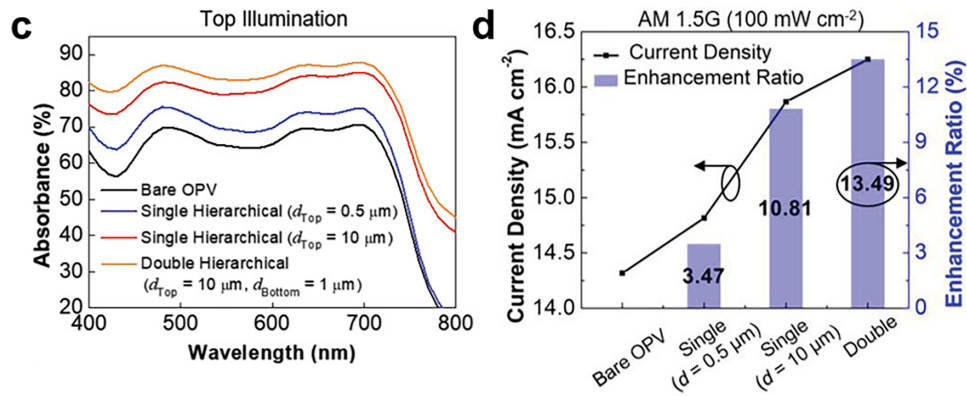


Figure 7: (a) Illustration of incident light from different incident angles; (b) reflectance spectra of the planar, submicron ($d = 0.5 \mu\text{m}$) and micron ($d = 10 \mu\text{m}$) hierarchical films; (c) measured absorbance of ST-OPV cells with/without hierarchical films under AM 1.5 G condition; (d) measured current density and its enhancement ratio of ST-OPV cells with/without hierarchical films under AM 1.5 G illumination [38].

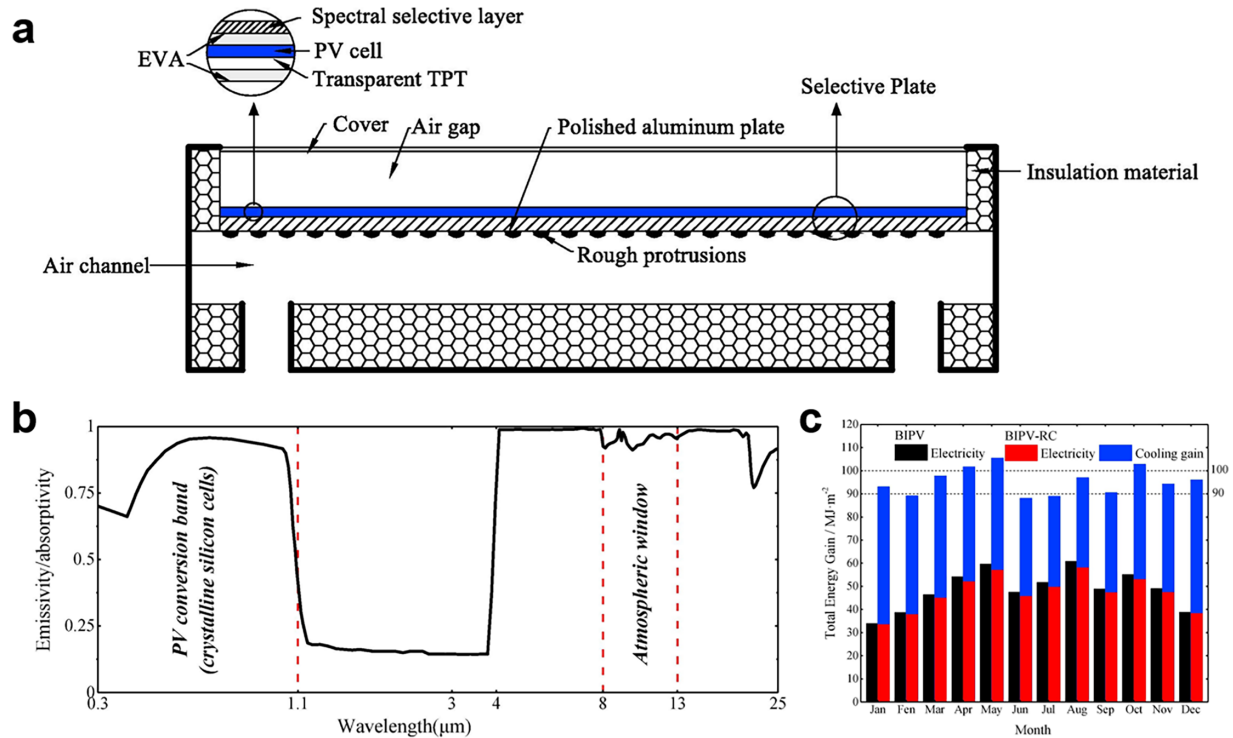


Figure 8: (a) Cross section of the BIPV module with spectral selective layer; (b) spectral emissivity/absorptance of the spectral selective plate; (c) annual energy gain comparison between the proposed system and ordinary BIPV system [40].

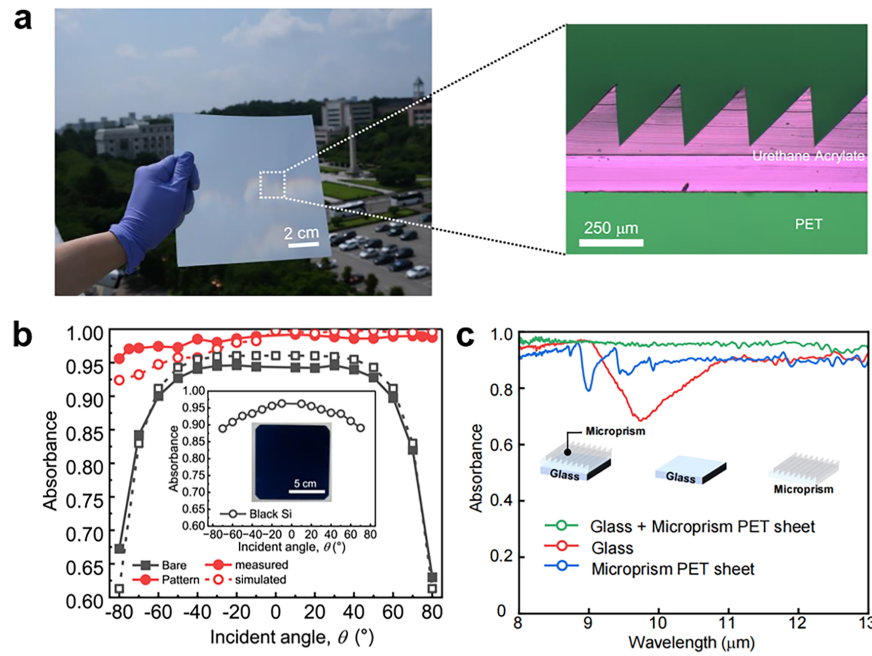


Figure 9: (a) Photograph (left) and optical microscopy image (right) of a fabricated microprism-imprinted PET sheet; (b) measured and simulated average absorbance of the surface-textured black Si with (pattern) or without (bare) microprism-coated glass cover at incident angles from 0° to 80°. The inset presents the measured angular absorbance of the normal black Si; (c) measured absorbance (8–13 μm) of the normal glass, microprism PET sheet, and microprism-coated glass [42].

Based on the specific optical perspectives, the core indicators reported in each study discussed in this section are summarized in Table 1.

Table 1: Previous studies related to BIPV optical properties.

Specific Fields	Core Indicators	References
Transmission of visible light	Decreased daily lighting energy consumption: 166 Wh; increased daily power generation: 1985 Wh	Peng et al. [32]
	Recommended PV etching ratio: 30%–50% for most cities; recommended cavity depth: 0.2 m	Liu et al. [33]
	Light utilization efficiency: 6.05%; highly transparent aesthetic reddish hue	Yu et al. [34]
Absorption of solar radiation	Increased captured irradiance: 7.63% within the visible spectrum, 6.91% within the near-infrared	Zhu et al. [35]
	Increased current density: 13.5% under AM 1.5G illumination	Lee et al. [38]

(Continued)

Table 1 (continued)

Specific Fields	Core Indicators	References
Emission within the atmospheric window	Increased total electricity generation plus cooling energy gains: 96.96%	Zhao et al. [40]
	Broadband, omnidirectional anti-reflection; emissivity close to unity across the atmospheric window	Kim et al. [42]

3 Thermal Properties

During the operation of PV cell, the generated heat raises PV cell temperature and reduces PCE (temperature dependent for common PV materials), and it can also produce unnecessary indoor heat gains, especially an important concern for buildings with large cooling demands [43,44]. Coupling PV with a thermal recovery subsystem (BIPV/T) provides a way to remove and utilize low-grade thermal energy, thereby improving overall building energy performance. For transparent BIPV, solar gain transmitted into the interior is characterized by the solar heat gain coefficient (SHGC), a key parameter in warm climates. In cold climates, although SHGC can provide heating, thermal transmittance (U-value) receives more attention because it describes the thermal insulating performance of building envelopes, significantly impacting the building heating loads [24]. This section reviews representative BIPV/T systems and approaches to regulating SHGC and U-value.

3.1 BIPV/T Systems

BIPV/T systems, which is capable of providing both electricity and useful heat for buildings, first emerged in the 1990s, although the general PV/T idea dates back to the 1970s [45,46]. Unlike stand-alone PV/T arrays, whose orientation and tilt can be optimized independently, BIPV/T layouts are constrained by architectural requirements and thus must balance building integration with thermal/electrical performance [47]. Based on the working fluid or heat transfer mechanism, BIPV/T solutions are typically classified as air-based, water-based, or phase change-based.

3.1.1 Air-Based Systems

Air-based BIPV/T designs exploit the readily available ambient air as the heat transfer medium, offering simplicity, low cost, and minimal risk of freezing or leakage. Fu et al. [48] investigated the thermal characteristics of an air-based BIPV/T façade system, as shown in Fig. 10a. The air channel was formed by spacing the BIPV module from the insulation layer to create a ventilated cavity. Their experiments showed that solar irradiance drives a pronounced chimney effect in the channel. The façade system exhibited a thermal shield effect, leading to a significant reduction in the heat transfer coefficient by roughly 65.3%–76% and low temperature fluctuations at the insulation interface.

3.1.2 Water-Based Systems

Because air has limited heat capacity and heat transfer capability [49], water-based BIPV/T systems are often used when stronger heat extraction or transport is required. As presented in Fig. 10b, Zhang et al. [50] demonstrated a water-cooled BIPV/T façade and integrated a water-source heat pump (HP) to upgrade the low-temperature fluid heat for space heating. Their BIPV/T-HP system improved outlet water temperatures sufficiently to contribute to building heating in winter, enhancing the overall utility of the harvested thermal energy.

3.1.3 Phase Change-Based Systems

Phase change materials (PCMs) are widely applied to manage PV temperatures because they provide high volumetric heat absorption without external energy input, acting as thermal buffers [51,52]. Ćurpek and Čekon [53] embedded an organic paraffin PCM layer within a ventilated BIPV façade, as displayed in Fig. 10c. Experimental results indicated that the PCM served as a thermal coat, increasing the thermal inertia of the assembly and effectively reducing the operating temperature of the PV module, thereby mitigating overheating and its adverse effects on PCE.

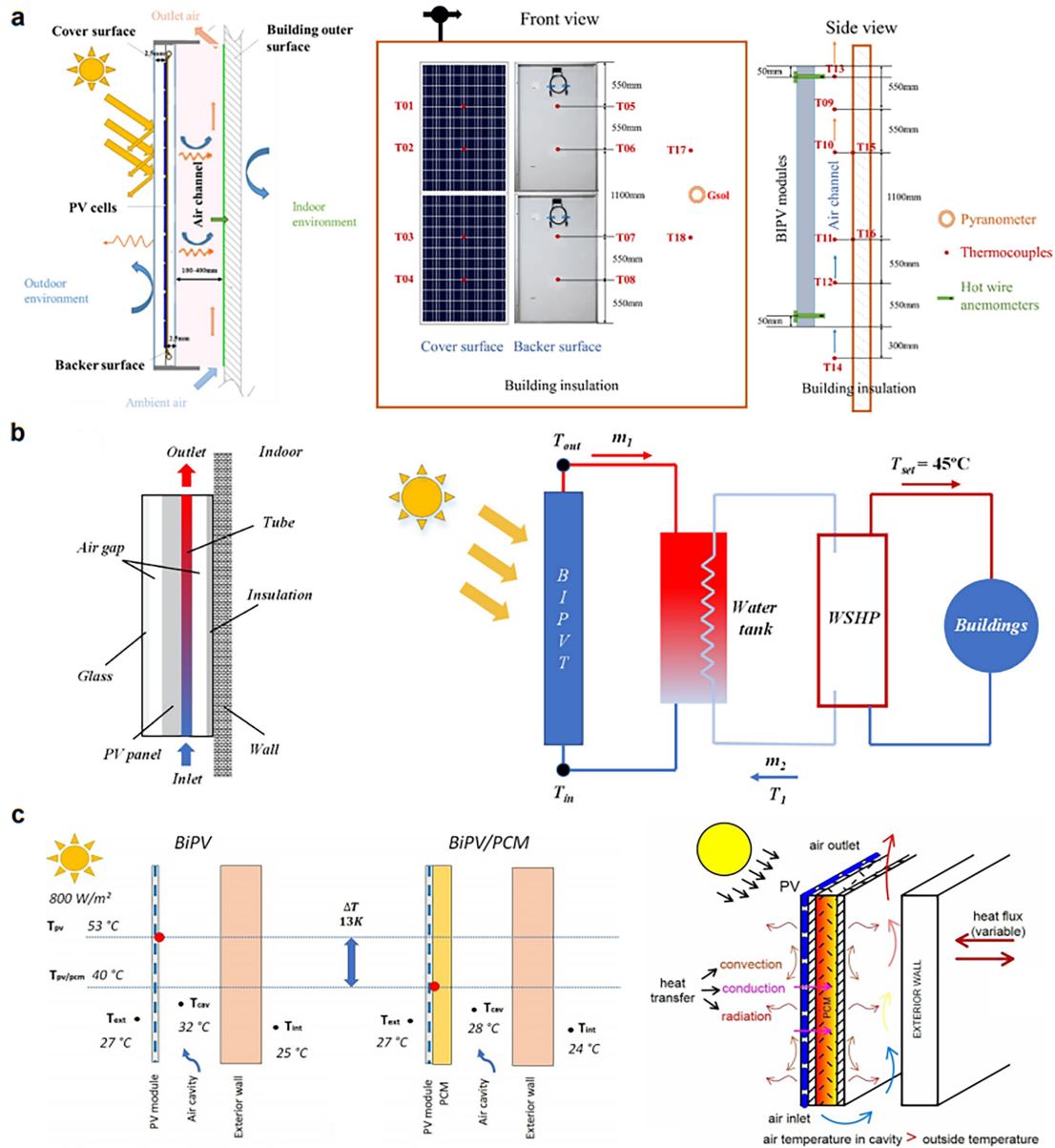


Figure 10: (a) Schematic diagram of air-based BIPV/T façade structure (left) and experimental setup (right) [48]; (b) Schematic diagram of water-based BIPV/T façade structure (left) and BIPV/T-HP system (right) [50]; (c) Schematic diagram of ventilated BIPV façade structure with/without PCM (left) and heat transfer process of BIPV/PCM ventilated façade (right) [53].

3.2 Regulation of Solar Heat Gain Coefficient

The solar heat gain coefficient (SHGC) quantifies the fraction of incident solar radiation on a transparent building element that is transmitted into the room as heat and is therefore a key metric for evaluating the thermal behavior of STPV systems [54]. Ventilation and cavity design strongly influence SHGC because they alter convective and radiative heat transfer between the STPV layer and the interior. Peng et al. [55] compared thermal performance for STPV façades under different ventilation modes (Fig. 11) and found that ventilated configurations best reduced solar heat gain while improving electrical output. Reported average SHGC values of ventilated, buoyancy-driven ventilated, and non-ventilated BIPV façades were about 0.1, 0.115, and 0.12, respectively. Compared to other modes, the daily power generation of ventilated BIPV façade had a maximum increase of 3%. As presented in Fig. 12, Preet et al. [56] experimentally examined the effect of air-cavity depth on SHGC in BIPV façades. Increasing the air cavity reduced radiative and convective heat transfer into the interior and thereby lowered SHGC. The effect was particularly pronounced under forced ventilation, where SHGC reduced from 0.213 at a 50 mm air cavity to 0.0172 at a 250 mm air cavity (air velocity 5 m/s). Enlarging the air cavity from 50 to 250 mm yielded power generation improvements of about 5.63% under natural ventilation and 8.72% under forced ventilation, respectively.

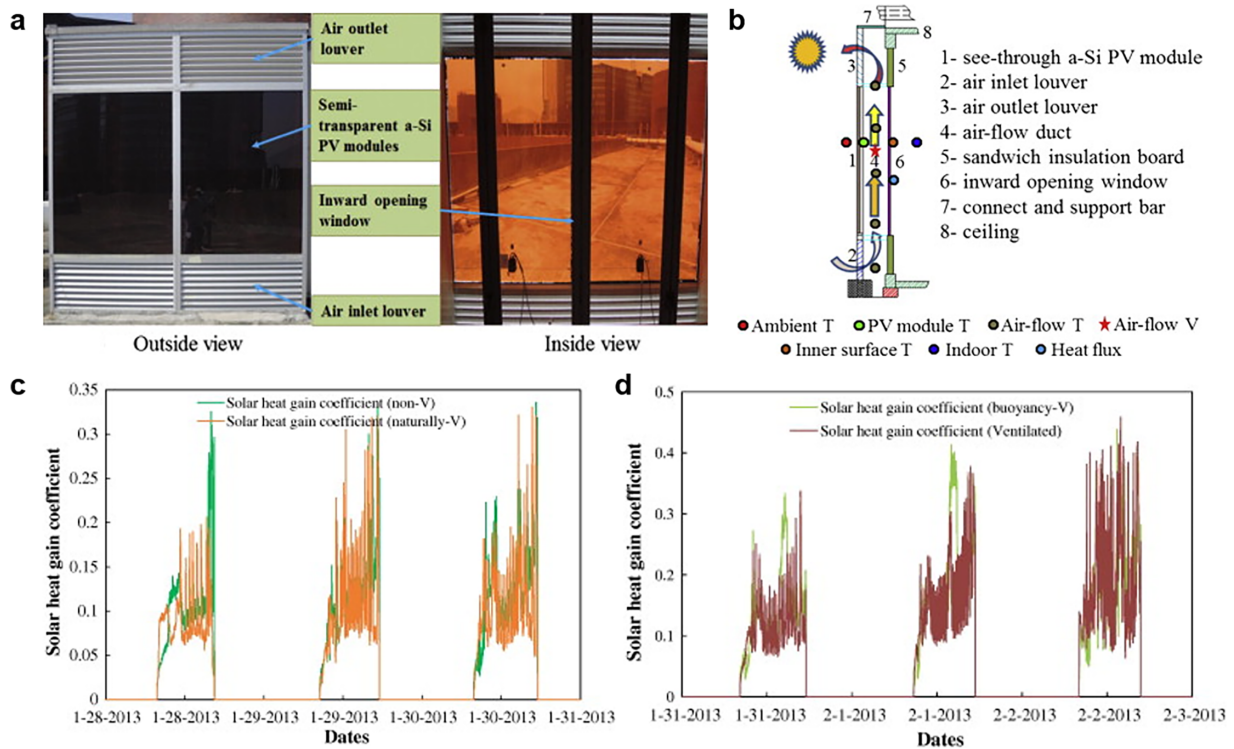


Figure 11: (a) photos of the ventilated BIPV façade system; (b) cross-sectional structure of the ventilated BIPV façade system; (c) comparison of SHGCs of BIPV façade under the ventilated and non-ventilated conditions; (d) comparison of SHGCs of BIPV façade under the ventilated and buoyancy-driven ventilated conditions [55].

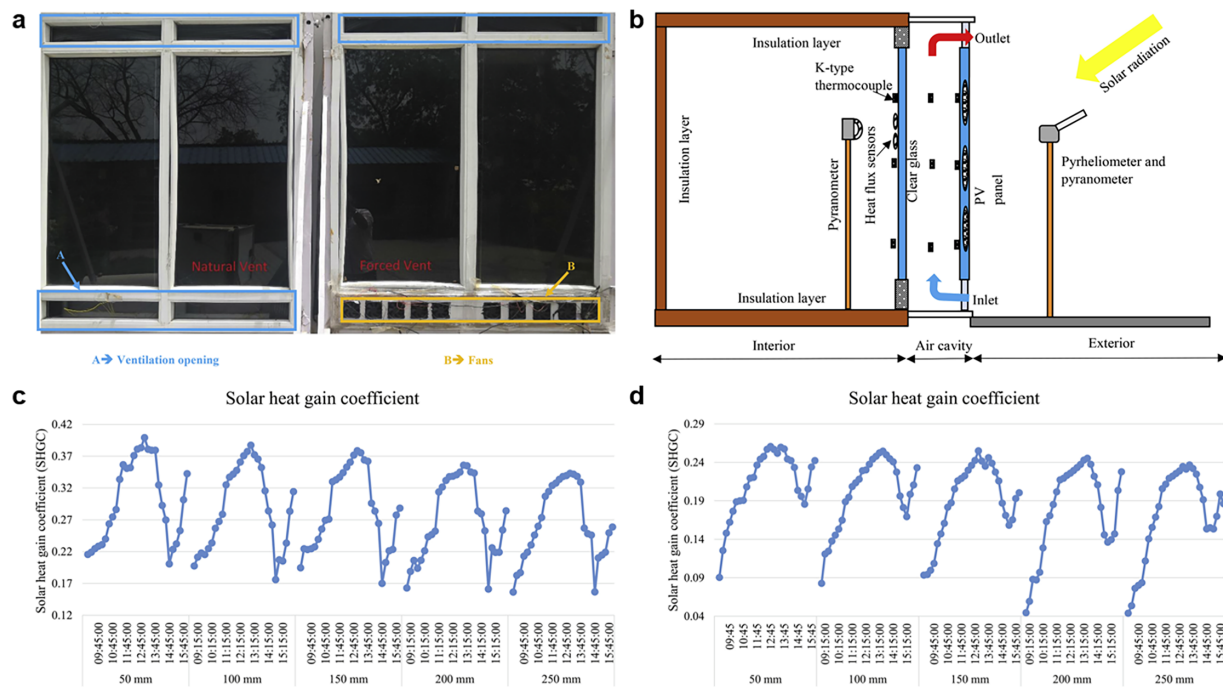


Figure 12: (a) photos of BIPV façade systems in the natural (left) and forced (right) ventilation modes; (b) schematic diagram of experimental setup; SHGCs of the (c) natural and (d) forced (5 m/s air velocity) ventilated BIPV façades at different air cavities [56].

These studies indicate that ventilated cavity designs are effective strategies for simultaneously reducing indoor solar heat gains and enhancing PV performance. However, designers must consider trade-offs such as façade depth, aesthetic and architectural constraints, and potential thermal comfort implications when selecting cavity dimensions and ventilation modes.

3.3 Regulation of U-Value

The U-value (thermal transmittance) quantifies heat transfer through an envelope element and is a primary determinant of heat loss in cold climates. Therefore, reducing U-value is central to lowering heating demand [55]. Material selection, glazing composition, cavity design, and integration of insulating technologies all influence the U-value of BIPV modules. Qiu et al. [57] proposed a vacuum BIPV insulated glazing unit that combines vacuum glazing with BIPV module (Fig. 13). Due to the very low U-value of about $1.5 \text{ W}/(\text{m}^2 \cdot \text{K})$, the vacuum BIPV IGU provided improved thermal insulation and helped maintain lower indoor temperatures. EnergyPlus and WINDOW simulations indicated that the south-facing unit could reduce building cooling load by 14.2% compared with a conventional BIPV façade.

In general, strategies to control U-value in BIPV systems include reducing transparency where acceptable, adopting advanced insulation technologies such as vacuum glazing, and optimizing cavity and frame design. The choice of approach depends on climate, orientation, daylighting requirements, and the balance between heating and cooling loads.

According to the specific thermal perspectives, the key metrics reported in each study discussed in this section are summarized in Table 2.

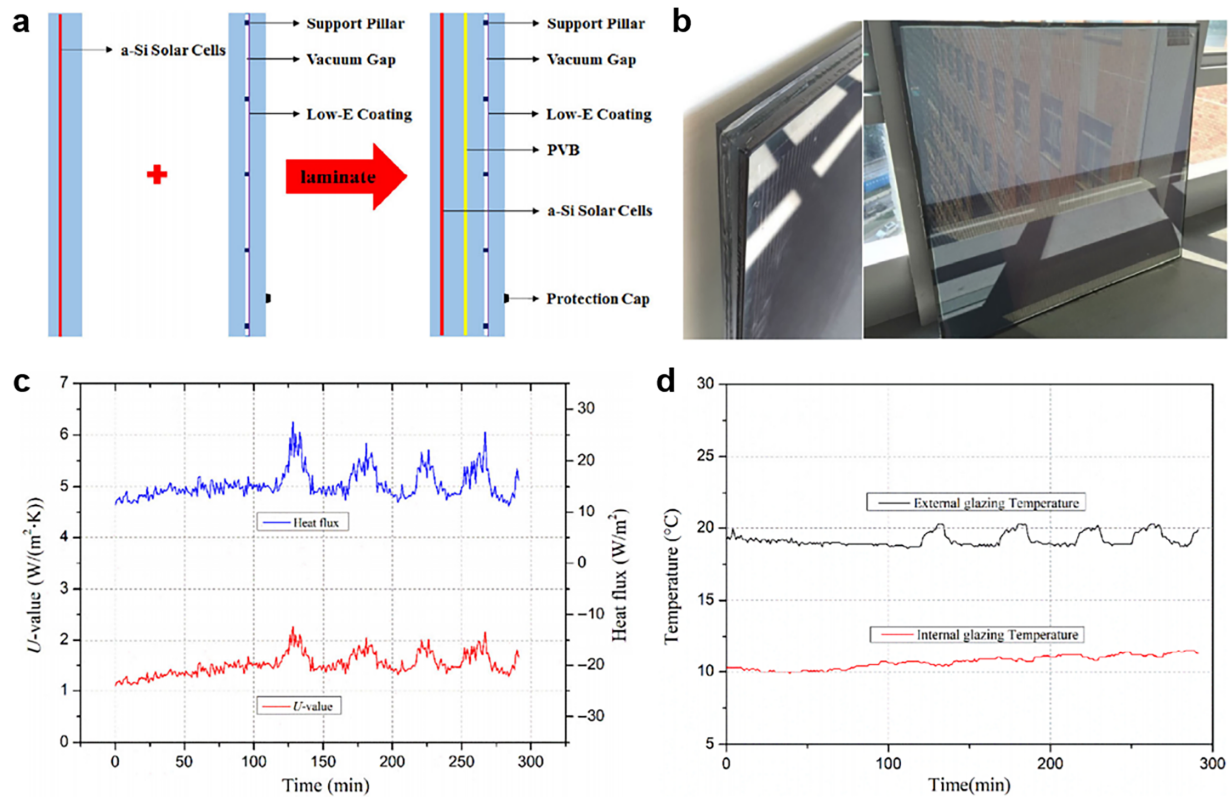


Figure 13: (a) Cross-sectional view of vacuum BIPV insulated glass unit; (b) photos of vacuum BIPV insulated glass unit; (c) measured heat flux and calculated U-value of the proposed unit; (d) internal and external glass temperature of the proposed unit [57].

Table 2: Previous studies related to BIPV thermal properties.

Specific Fields	Core Indicators	References
Air-based BIPV/T	Reduced heat transfer coefficient: 65.3%–76%	Fu et al. [48]
Water-based BIPV/T	Enhanced the overall utility of the harvested thermal energy	Zhang et al. [50]
Phase change-based BIPV/T	Increased the thermal inertia thus mitigating overheating	Čurpek and Čekon [53]
Regulation of SHGC	SHGC values of ventilated, buoyancy-driven ventilated, and non-ventilated BIPV façades: 0.1, 0.115, and 0.12, respectively	Peng et al. [55]
	SHGC reduced from 0.213 at a 50 mm air cavity to 0.0172 at a 250 mm air cavity (air velocity 5 m/s)	Preet et al. [56]
Regulation of U-value	Reduced building cooling load: 14.2% for the south-facing unit with a very low U-value of 1.5 W/(m²·K)	Qiu et al. [57]

4 Electrical Properties

As the principal performance metric for PV systems, power generation has been the focus of extensive research. For BIPV, however, electrical performance should be considered more broadly: in addition to on-site electricity production, some BIPV designs change building energy consumption (lighting, cooling and heating). These consumption changes are therefore part of the net electrical benefit of a BIPV deployment. Design constraints needed to fulfill envelope requirements, such as daylighting, fire, watertightness, aesthetics, and so on, sometimes reduce electrical performance relative to standard PV modules [58]. Beyond cell technology and cell coverage ratio, several factors substantially influence BIPV electrical behavior and the building energy consumption. For instance, thermal management/cooling (BIPV/T), window-to-wall ratio (WWR) for BIPV glazing [59], shading from adjacent objects or the building itself [60], and module layout/orientation [61]. Generally, in the Northern Hemisphere, tilted and south-facing modules performing better electrical performance [62]. The following subsections summarize key findings on coverage ratio, WWR, and shading effect, with emphasis on both power output and impacts on building energy consumption.

4.1 Cell Coverage Ratio

The fraction of a PV module covered by solar cells sets gross generation potential, but transparent BIPV must trade coverage for daylighting. Quantifying this trade-off helps choose coverage that balances electricity production with indoor lighting and thermal loads. Karthick et al. [63] investigated STPV skylights with cell coverage ratios of 0.62, 0.72, and 0.85, as shown in Fig. 14. They identified an optimum at 0.72 for combined daylighting performance and cooling load reduction, which delivered the lowest annualized cost of 0.035 \$/kWh. As illustrated in Fig. 15, Xu et al. [64] showed PCE of STPV modules falls as coverage ratio increases: a reported nearly 5.5% decrease in PCE when coverage ratio rise from 10% to 80%. Higher coverage ratio also reduces indoor daylight illuminance and thus raises electric lighting use. When both generation and consumption are considered, for generic office buildings, selecting an optimal coverage can yield overall electricity savings up to 30% compared with the least favorable coverage choices.

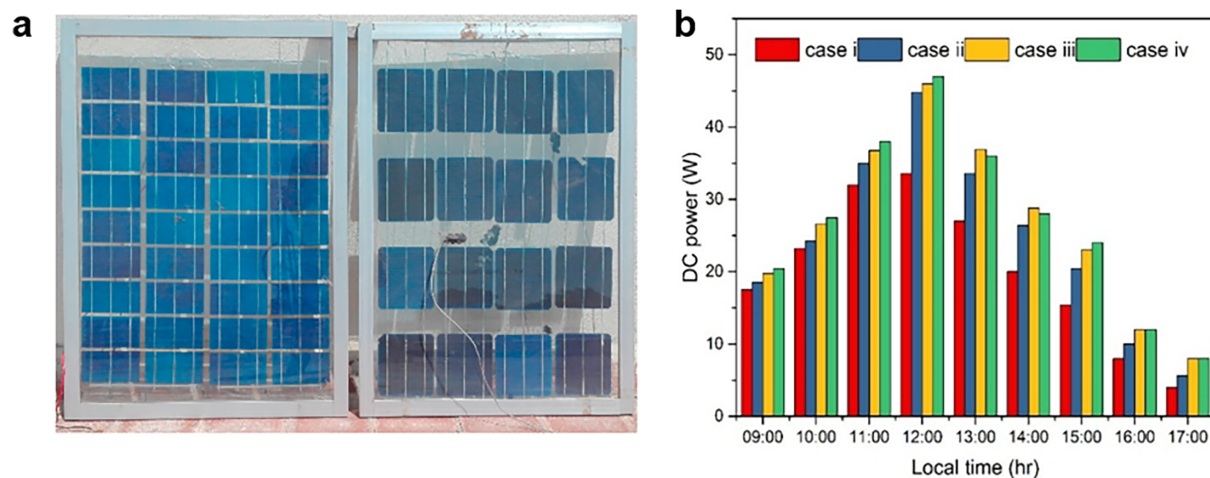


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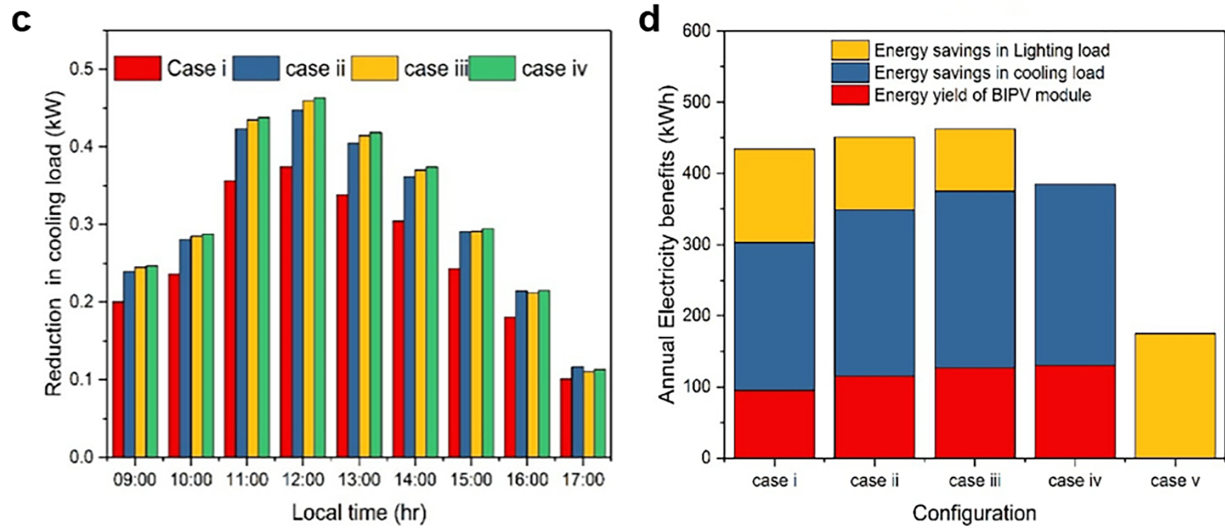


Figure 14: (a) Photos of STPV skylights with PV cell coverage ratio of 0.72 (left) and 0.62 (right); average hourly (b) electrical power and (c) reduction in cooling load of STPV skylights in summer; (d) annual electricity benefits of STPV skylights [63].

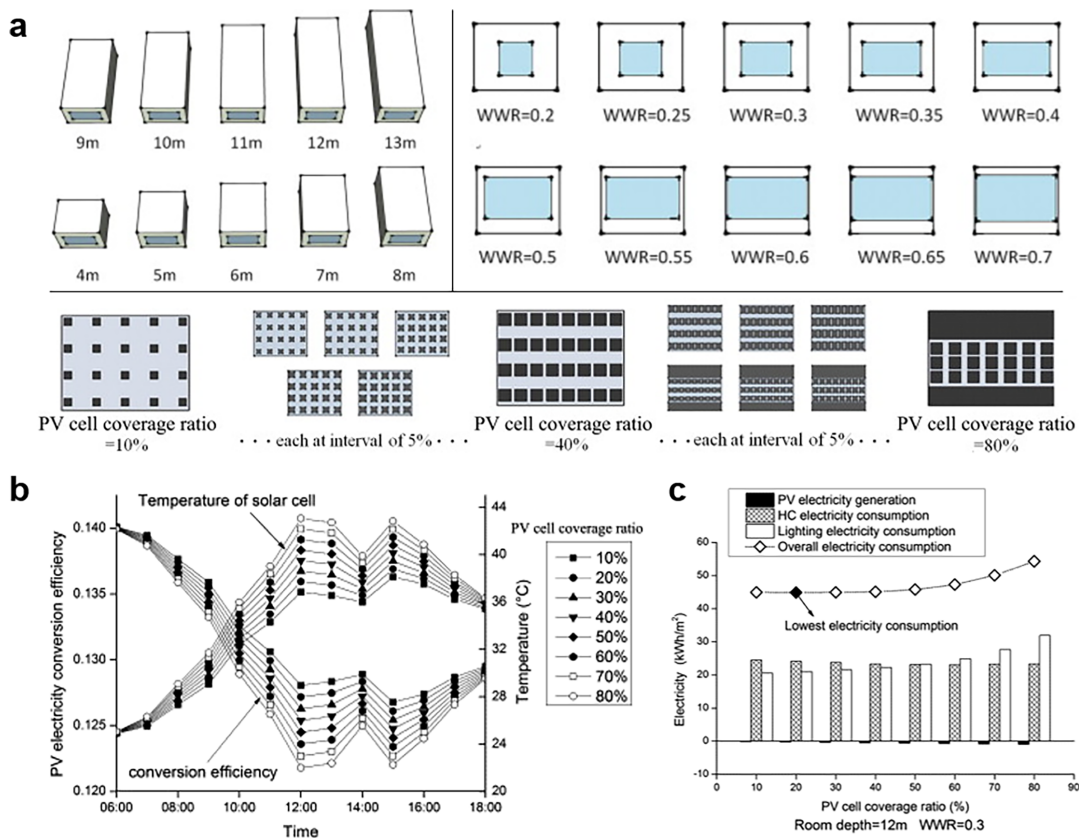


Figure 15: (a) Illustration of variations in room depth, WWR, and PV cell coverage ratio; (b) solar cell temperature and PCE of the STPV module with different PV cell coverage ratio; (c) changes in overall energy consumption with different PV cell coverage ratio (room depth = 12 m, WWR = 0.3) [64].

4.2 Window-to-Wall Ratio

WWR (window area divided by façade area) strongly influences daylighting and thermal loads when the windows are the weakest components in the heat transfer process of vertical envelopes [65]. Regarding BIPV windows, WWR changes both electricity generation area and the lighting/heating/cooling demands of buildings. Sun et al. [66] developed an integrated optical-electrical-energy model for CdTe PV glazing (Fig. 16). As WWR increased from 45% to 75%, the energy-saving potential of PV glass grew due to the significant reduction in cooling energy consumption. The largest energy saving occurred for 80% PV glass replacement at 75% WWR. They also reported that, for large window fractions covered by PV glass, net energy performance under cold climates can exceed that in hot climates because the reduced heating loads and additional generation can outweigh increased lighting loads.

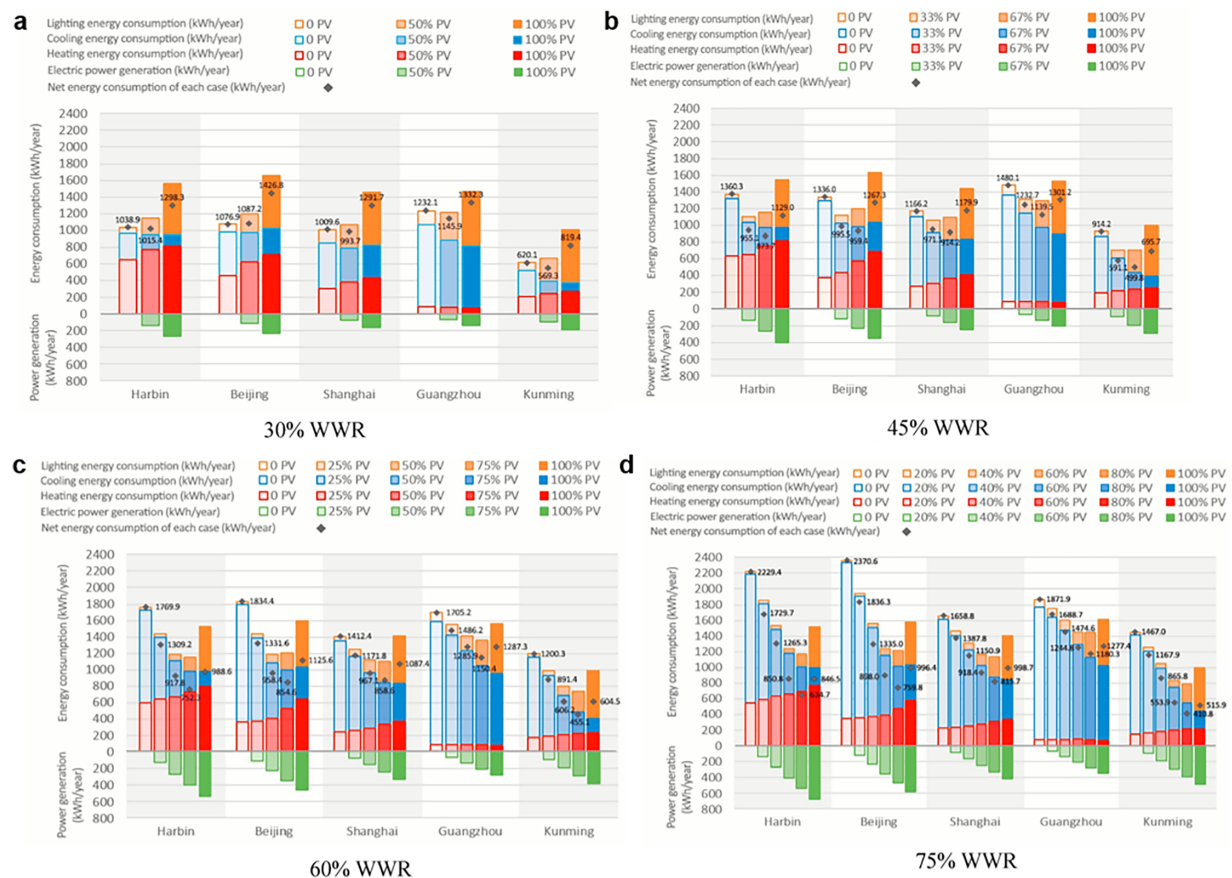


Figure 16: Energy performance of BIPV window system with CdTe PV glass for (a) 30% WWR; (b) 45% WWR; (c) 60% WWR; (d) 75% WWR [66].

4.3 Shading Effect

Partial shading is a frequent and important limitation for BIPV electrical performance because façades and urban installations are more likely to be partially shaded by neighboring buildings, self-shading elements, balconies, or architectural features [67]. Partial shading reduces string output and can create localized reverse bias and heating (hot-spot effect), potentially damaging cells or modules under strong irradiance [68]. Standard protective measures include bypass diodes (for series-connected modules) and blocking diodes (for parallel-connected modules) to limit reverse stresses and reduce mismatch losses [69].

Micro-inverter is another solution, enabling each module to operate at its maximum power point independently [70,71]. Beyond electrical protection, intelligent reconfiguration and control can mitigate shading impacts. As displayed in Fig. 17, based on the predictions using Building Information Modeling (BIM), Shao et al. [72] reported that appropriate reconfiguration strategies can improve annual power generation by nearly 5%–10% relative to fixed conventional layouts. Among conventional electrical wiring topologies, Total-Cross-Tied configurations often provide the best compromise for minimizing losses from static or dynamic partial shading.

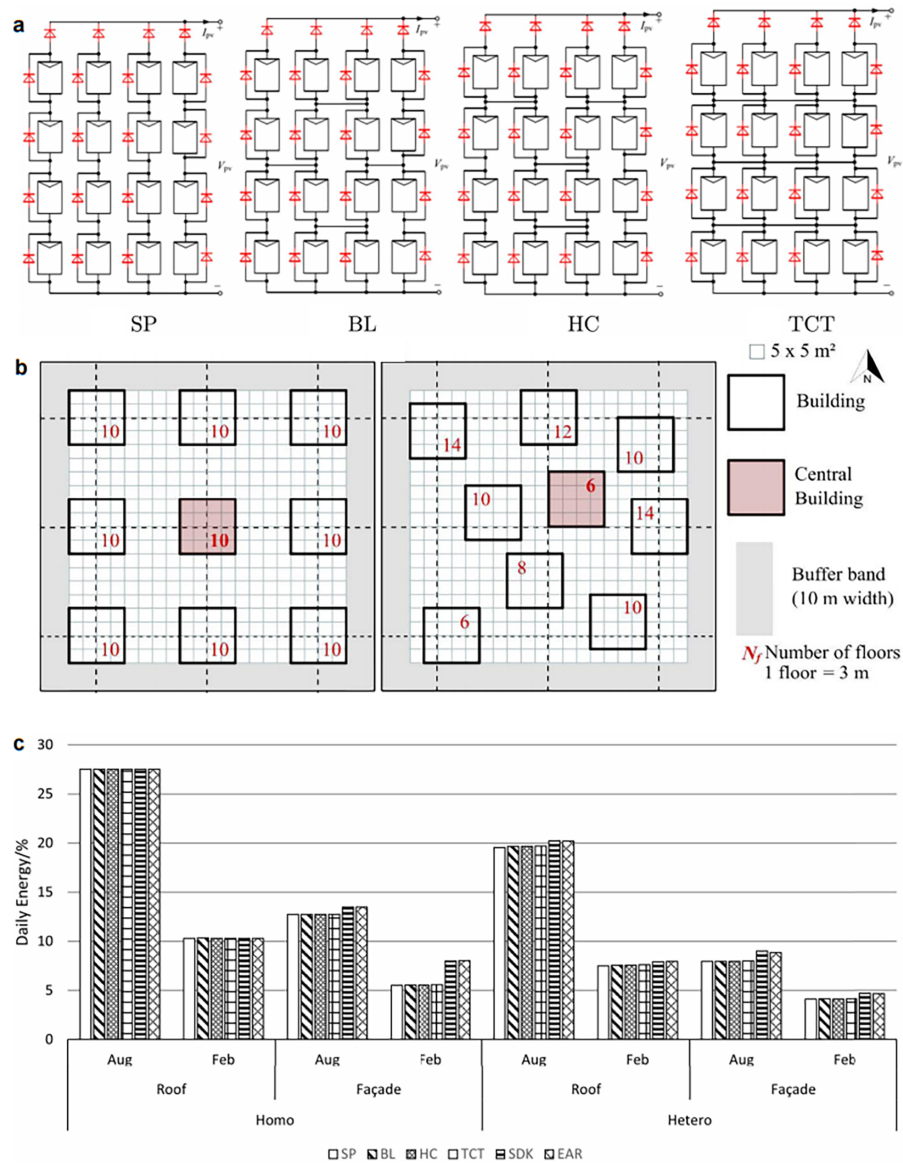


Figure 17: (a) The four conventional PV configurations (SP: Series-Parallel; BL: Bridge-Link; HC: Honey-Comb; TCT: Total-Cross-Tied); (b) illustration of homogeneous (left) and heterogeneous (right) distributions; (c) daily power generation of BIPV roof/façade systems with various PV configurations in homogeneous and heterogeneous districts (SDK: Sudoku; EAR: Electrical Array Reconfiguration) [72].

Based on the specific electrical perspectives, the core indicators reported in each study discussed in this section are summarized in [Table 3](#).

Table 3: Previous studies related to BIPV electrical properties.

Specific Fields	Core Indicators	References
Cell coverage ratio	Combined daylighting performance and cooling load reduction: 0.72 cell coverage ratio delivered the lowest annualized cost of 0.035 \$/kWh	Karthick et al. [63]
	Overall electricity savings with the optimal coverage for generic office buildings: 30%	Xu et al. [64]
WWR	Largest energy saving occurred: 80% PV glass replacement at 75% WWR	Sun et al. [66]
Shading effect	Increased annual power generation using appropriate reconfiguration strategies: 5%–10%	Shao et al. [72]

5 Conclusions and Prospects

Building-integrated photovoltaics (BIPV) transforms building envelopes, such as roofs, façades, windows, and sunshades, into active energy-producing elements while simultaneously serving traditional envelope functions. This dual role imposes multi-objective requirements beyond conventional PV performance: optical (daylighting, visible transmittance, spectral behavior), thermal (cooling, heat gain, thermal transmittance), and electrical (power generation, mismatch and shading resilience) properties must all be considered alongside architectural constraints. This review summarized the state of knowledge on those energy-related behaviors and their impacts for building energy efficiency.

Visible transmittance is a defining metric for transparent BIPV. Properly designed semi-transparent photovoltaic (STPV) can provide useful daylighting, reducing electric lighting demand while requiring a trade-off with cell coverage and power conversion efficiency (PCE). Optical surface engineering (micro/nano structures, hierarchical films, micropisms, spectral selective layers) can significantly improve solar capture by reducing reflection over wide incident angles and by tailoring spectral absorptance. These measures also enable combined functions such as selective solar absorption and mid-infrared emissivity enhancement for radiative cooling. Mid-infrared emissivity across the atmospheric window (8–13 μm) is an emerging design parameter: combining high solar absorptance with good atmospheric-window emissivity can enable passive cooling strategies that reduce module temperature and improve electrical output, especially when façades are adapted to overcome oblique sky view limitations.

Thermal management is essential. Heat generated in PV modules reduces PCE and can increase indoor cooling loads for glazed BIPV. BIPV/T systems are effective for extracting and using low-grade heat, lowering module operating temperatures and improving overall building energy performance. Solar heat gain coefficient (SHGC) and U-value (thermal transmittance) remain central window metrics when BIPV replaces glazing. Ventilated cavity designs, larger air gaps, and advanced insulating glazing can substantially reduce SHGC or U-value as required by climate and orientation. Optimal choices are climate- and use-dependent: limit SHGC in hot climates and prioritize low U-values in cold climates.

Electrical performance must be assessed comprehensively as net building electrical benefit: power generation minus changes in building electricity consumption (lighting, heating, and cooling). Important

drivers include cell type, cell coverage ratio, window-to-wall ratio (WWR), module orientation/tilt, and shading effect. Partial shading and non-uniform irradiance are common for BIPV and can cause disproportionate power loss and hot-spot risks. Mitigation measures include bypass/blocking diodes, reconfiguration strategies, and early shading analysis through software tools.

This review clarifies the energy-related behaviors and application potential of BIPV systems. However, there are still barriers to the deployment of BIPV systems in terms of standard, economic, and aesthetic considerations. Beyond technical PV performance, based on the actual application scenario and building types, it is necessary to further emphasize its universal properties such as architectural integration, cost-effectiveness, and aesthetic design in the future.

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