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Semitransparent and Colorful Solar Cell for Architectural Application

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ABSTRACT

Semitransparent and colorful solar cells (STC-SCs) offer a transformative solution for architectural applications by merging energy generation with aesthetic value. Unlike traditional opaque solar panels, these advanced cells allow light transmission while efficiently harvesting solar energy, making them ideal for integration into windows, facades, and other architectural elements. As buildings increasingly emphasize energy efficiency and sustainability, STC-SCs present a promising opportunity to generate renewable energy without sacrificing natural light or visual appeal. This review explores the potential of these solar cells in architectural settings, highlighting their integration in various building applications. It examines the underlying principles of photovoltaics, the materials used in the development of STC-SCs, the performance of lab-scale STC-SCs and the research gap and challenges. The review concludes by identifying future research directions and emphasizing the role of STC-SCs in advancing sustainable building technologies and fostering innovation in the field of building-integrated photovoltaics.

1. Introduction

Semitransparent and colorful solar cells (STC-SCs) represent an advanced technology that combines aesthetic appeal with energy generation, making them highly suitable for applications in building-integrated photovoltaics (BIPVs), wearable electronics, and other innovative uses [1-4]. These solar cells are designed to allow light to pass through while simultaneously converting sunlight into electricity, offering a dual functionality of transparency and power generation [5,6]. This feature makes STC-SCs particularly valuable for architectural applications, where both energy efficiency and visual appeal are essential.

A key feature of STC-SCs is their customizable nature, which allows variations in both color and transparency. This flexibility enables architects to incorporate these solar cells into building designs without compromising on aesthetics. Whether used in windows, facades, or interior elements, STC-SCs can be tailored to complement the architectural style of a building, all while contributing to its sustainability objectives. Available in a wide array of colors and designs, these solar cells provide an

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innovative solution that addresses the growing demand for renewable energy solutions in the built environment, enhancing both environmental performance and visual integration.

The development of bifacial STC-SCs that cells capable of capturing light from both the front and rear surfaces further enhances their energy efficiency, especially in environments with highly reflective surfaces [7,8]. This bifacial feature proves especially advantageous for applications such as floating solar arrays and agrivoltaic systems, where maximizing light absorption is crucial.

In this review, we will explore the application of STC-SCs in architectural design, followed by an overview of the fundamental principles behind their operation and the materials used in their fabrication. We will also address the challenges associated with these devices and discuss their future potential in the renewable energy landscape.

2. Applications of STC-SCs in Architectural Design

The primary applications of STC-SCs in architecture are found in building facades and roofs. These applications leverage the dual functionality of STC-SCs. In this section, we present several real-world examples that demonstrate the integration of STC-SCs into architectural designs, highlighting their potential to enhance sustainability, visual appeal, and energy efficiency in modern buildings.

In Figure 1(a) shows STC-SCs have been successfully integrated into BIPVs as facades, installed on the west façade of the SwissTech Convention Center at the École Polytechnique Fédérale de Lausanne (EPFL). The façade was manufactured by Solaronix by assembled 1500 Dye-Sensitized Solar Cells (DSSC) modules of 35 x 50 cm on surface of 300 m2. In Figure 1(b), the panel provides an interior view of the convention center, showcasing the solar panel's ability to allow natural light penetration while simultaneously generating electricity. In contrast, in Figure 1(c), the panel offers an external view, emphasizing how the panel contributes to the building’s overall aesthetic while maintaining functional transparency. This example underscores the potential of STC-SCs to enhance both the visual and energy performance of modern architectural designs [9].

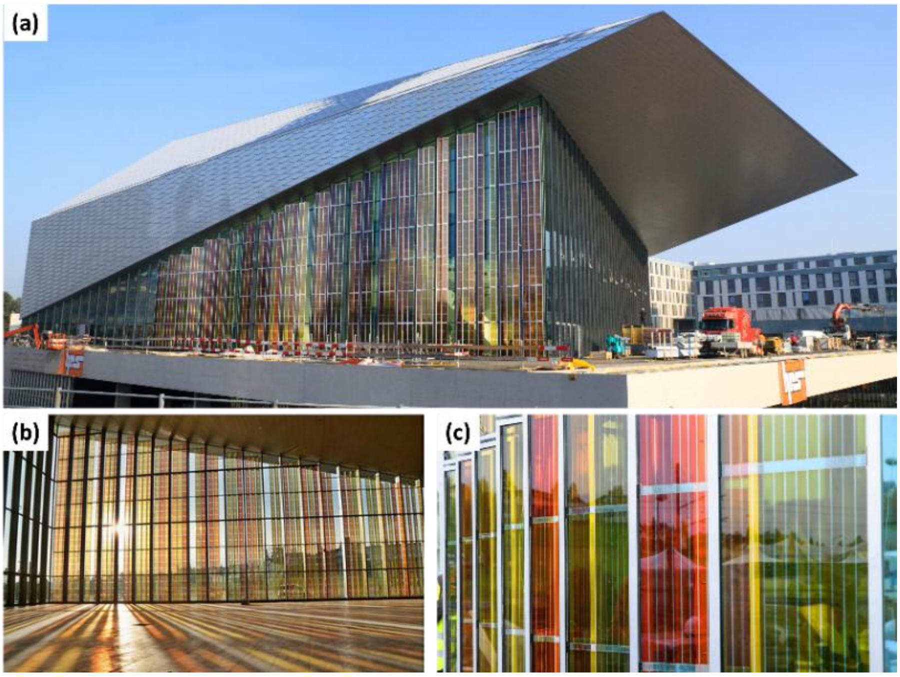

Fig. 1. (a) Semitransparent colored solar panel integrated into the west façade of the SwissTech Convention Center at École Polytechnique Fédérale de Lausanne (EPFL) (b) Image captured from inside the convention center, illustrating the panel's light transmission and aesthetic integration [10] (c) Image captured from outside, showcasing the panel's contribution to the building's exterior design [11]

In Figure 2 showcases the integration of semitransparent solar panels into the façade of the Life Sciences Building at the University of Washington. The translucent amorphous silicon (a-Si) film laminated in the vertical glass fins will generate enough solar power to supply all the lighting for the offices in the building, with the 12,400 square feet of solar glass fins producing electricity year-round. Figure 2(a) illustrates the installation of the solar panel on the building's exterior, highlighting its role in providing both energy generation and architectural enhancement. Figure 2(b) presents an interior view, demonstrating how the semitransparent nature of the panel allows natural light to pass through while maintaining the building's aesthetic appeal. The ability of the panel to blend light transmission with power generation is critical for creating a comfortable and sustainable indoor environment and Figure 2(c) provides an external perspective of the building, emphasizing how the solar panels seamlessly contribute to the overall architectural design, demonstrating their potential to enhance both the functionality and visual integration of building envelopes [12].

Fig. 2. (a) Installation of a semitransparent solar panel on the façade of the Life Sciences Building at the University of Washington (b) Interior view demonstrating the panel’s ability to transmit light while complementing the building’s design (c) Exterior view highlighting the panel’s integration into the overall architectural aesthetic of the building [13]

BIPV systems have been successfully implemented in various roof applications. Figure 3 illustrates the integration of BIPV roofs in two distinct architectural settings. Figure 3(a) the roof of Berlin Train Station is shown, where solar panels not only enhance the station's energy efficiency but also seamlessly blend with its modern architectural design. A system of 780 solar modules, featuring 78,000 transparent, powerful solar cells, was installed on the East-West hall roof, integrated into the glass surfaces. This setup allows for both energy generation and the continuation of natural daylight on all three levels of the station. The transparency of the panels filters natural light, enriching the station's interior while providing a sustainable energy solution for this high-traffic transportation hub [14]. In Figure 3(b) showcases the BIPV roof at Tanjong Pagar Centre Urban Park, situated within a bustling urban environment in Singapore. Here, the semitransparent solar panels are incorporated into the design of an urban green space, demonstrating the versatility of BIPV technology in outdoor settings. The huge PV canopy, covering over 2,600 m² at the building's main entrance, is composed of more than 850 units of a-Si PV glass. This canopy generates energy on-site while also filtering harmful radiation to provide shade and comfort for visitors. It produces enough energy to power over 7,000 light points within the building. By integrating these panels into the park’s roof, the project not only generates renewable energy but also enhances the overall sustainability of the space, offering both functional and aesthetic benefits to the surrounding community [15].

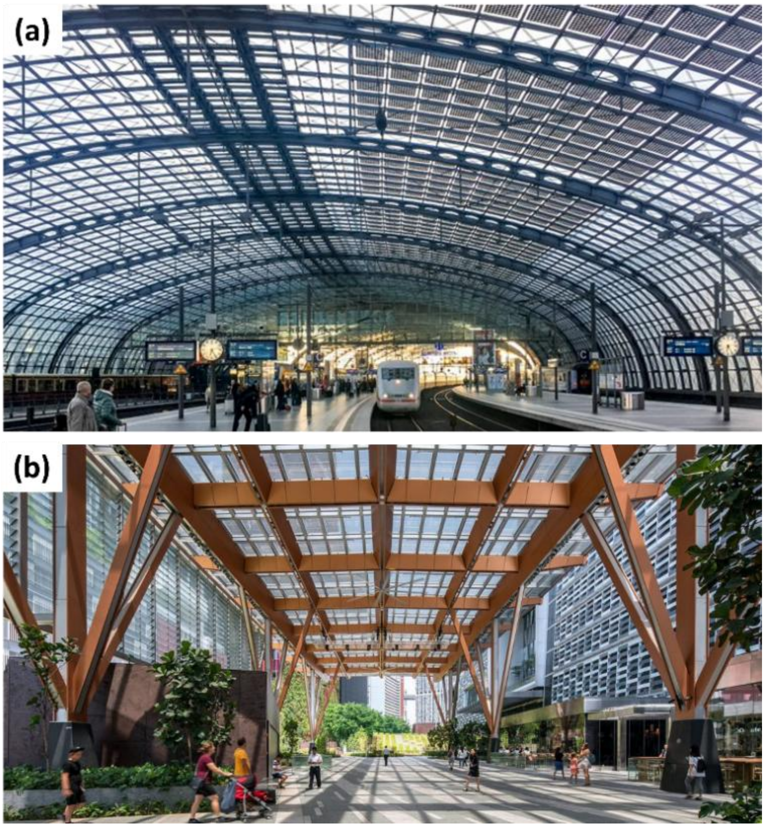

Fig. 3. Semitransparent BIPV roofs (a) Berlin Train Station, showcasing the integration of BIPV in a transportation hub [16] (b) Tanjong Pagar Centre Urban Park, highlighting the use of BIPV in an urban green space [15]

3. Principle and Materials used in STC-SCs

3.1 Basic Principle of Solar Cells

At the core of solar cell technology is the PV effect, which converts light energy into electrical energy. This process begins when photons from sunlight hit the solar cell's surface and absorb by its photoactive materials, exciting electrons and causing them to break free from and form free charges. These free holes and electrons flow through the material, creating an electric current. The efficiency of a solar cell is measured by its Power Conversion Efficiency (PCE), which indicates how effectively the cell converts sunlight into electricity, calculated as the ratio of the electrical power output to the incoming sunlight power. Short-Circuit Current Density (J_{SC}) measures the current generated per unit area of the cell when its terminals are short-circuited, reflecting how effectively the cell absorbs light and generates electrons. Open-Circuit Voltage (V_{OC}) is the maximum voltage the cell can produce when there is no current flow, influenced by the material’s properties and bandgap. Fill Factor (FF) is the ratio of the maximum power output to the theoretical maximum power, indicating how well the solar cell performs at its optimal operating point. Together, these parameters, PCE, J_{SC}, V_{OC}, and FF give a complete measure of a solar cell’s performance, with higher values indicating greater efficiency and energy conversion.

3.2 Basic Principle of STC-SCs

Transforming to STC-SCs involves selecting materials with high absorption coefficients and optimizing the electrical and optical properties of the cells. These semitransparent cells are designed to allow a portion of light to pass through while simultaneously capturing some light for energy conversion. Unlike traditional opaque solar cells, which absorb nearly all incoming light, STC-SCs permit light transmission, making them ideal for use in windows, facades, and other architectural features that require light permeability. Figure 4 shows the difference of spectral response of opaque solar cell and transparent solar cell, where in transparent solar cell, the device does not absorb at visible wavelength region.

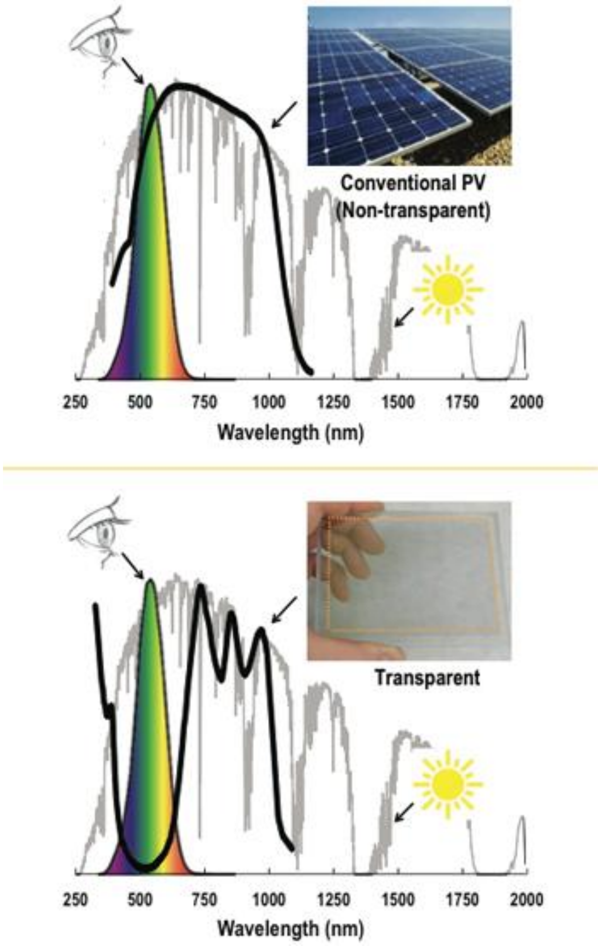

Fig. 4. Spectral response of conventional (opaque) and transparent solar cell [17]

3.3 Materials used in STC-SCs

The selection of materials is a critical factor in the design and performance of solar cells. The basic structure of a typical solar cell consists of a transparent substrate and transparent conductive electrodes (front contact), followed by a photoactive layer and an electrode (back contact). In Organic Solar Cells (OSCs) and Perovskite Solar Cells (PSCs), charge transport layers, specifically Electron Transport Layer (ETL) and the Hole Transport Layer (HTL) are employed to facilitate the efficient movement of charge carriers between the front and back contacts. In DSSCs, both an interlayer and an electrolyte are utilized to promote the flow of charges between the electrodes, enabling the cell to generate power efficiently. In contrast, inorganic solar cells, such as silicon-based cells, commonly incorporate an anti-reflective coating to minimize light reflection and enhance overall efficiency by maximizing light absorption.

Front contact consist of transparent or semitransparent conductive electrodes are essential components, as they must provide both electrical conductivity and optical transparency. Materials such as indium tin oxide (ITO), fluorine-doped tin oxide (FTO), doped graphene, and ultrathin or nanowire metal films are commonly used [18-20]. These materials are selected for their ability to maintain high conductivity while allowing light to pass through.

The photoactive layer is the most crucial component in solar cells, as it is responsible for absorbing light and converting it into electrical energy. Among the most promising materials for solar cell technologies are organic, perovskite, dye-sensitized, and silicon-based materials. Figure 5 presents the highest reported research cell efficiencies, as compiled by the National Renewable Energy Laboratory (NREL). The highest PCE achieved are 19.2% for OSCs, 27.0% for PSCs, 13.0% for DSSCs, and 27.6% for Si-SCs [21].

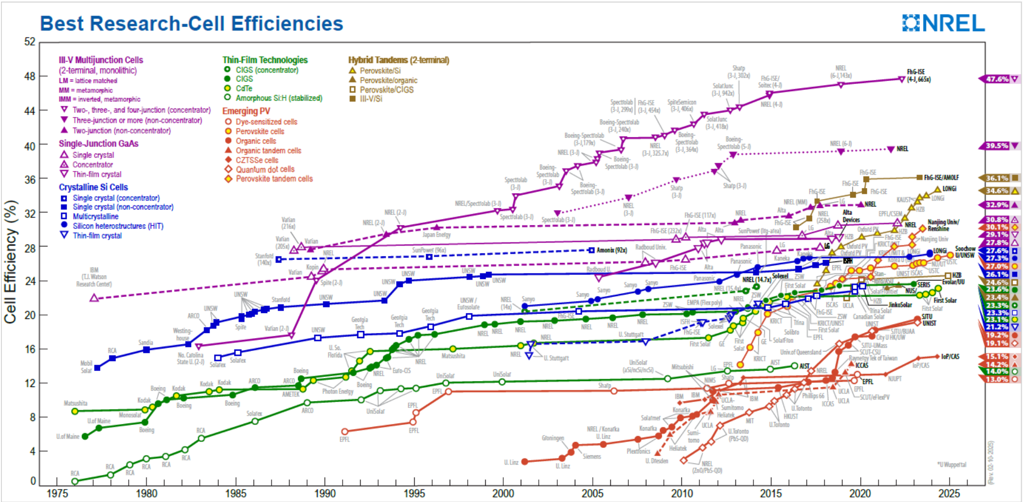

Fig. 5. Best research-cell efficiency chart

In comparison to inorganic solar cells, organic materials offer significant potential for STC-SCs, primarily due to their flexibility, ease of fabrication, and customizable optical properties [22]. Materials like conjugated polymers or small molecule donors can be easily fabricated with fullerene and non-fullerene acceptors in a solution-based process before being formed into films that function to absorb light and convert it into electrical energy [23-26]. A key advantage of organic materials is their capacity for tailored engineering, enabling precise control over optical characteristics and energy bandgap. By adjusting the composition of these materials, manufacturers can modulate the absorption spectrum, achieving a diverse range of colors without compromising performance. Figure 6(a) shows the energy level diagram of organic polymer donor and non-fullerene acceptor. Perovskite materials have garnered significant attention due to their high PCE and straightforward fabrication process [27,28]. These materials, often based on lead halides and more recently on non-toxic alternatives such as tin halides, exhibit excellent light absorption properties. Perovskites are particularly well-suited for STC-SCs because their bandgap can be tuned by adjusting the composition of the perovskite layer, allowing for precise control over their transparency and color (Figure 6(b)). DSSCs consist of a porous titanium dioxide (TiO_2), a sensitizing dye that absorbs light, and a liquid or solid electrolyte [29,30]. The dye molecules are key to determining the color of the solar cell, as they absorb specific wavelengths of light and generate charge carriers that are transferred to the TiO_2 electrode for electricity generation.

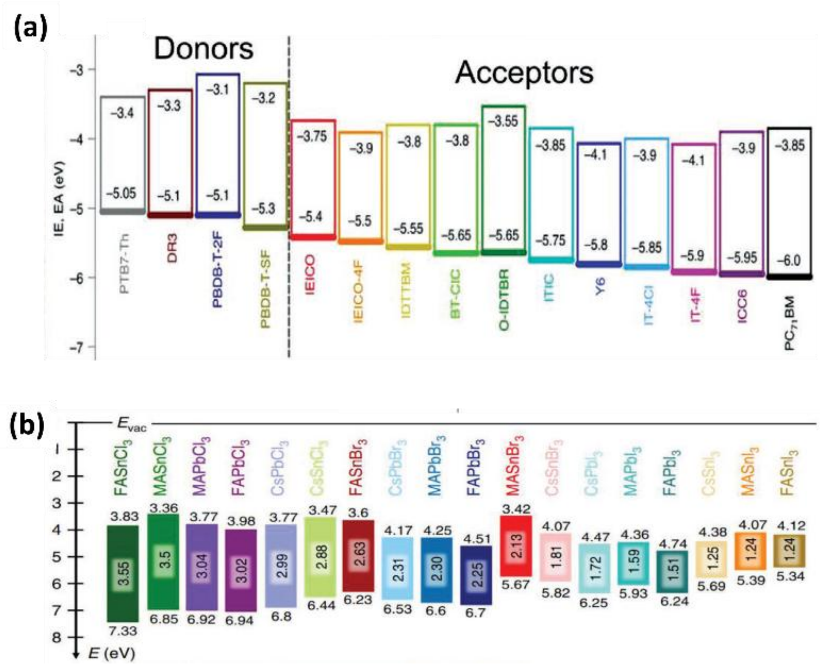

Fig. 6. (a) Schematic energy level diagram of polymer and non-fullerene acceptor used in OSC (Reproduce with permission from ref [31] Copyright 2021, Springer Nature) (b) Schematic energy level diagram of different metal halide perovskites (Reproduced under the terms of the CC BY license [32] Copyright 2019, Springer Nature)

Another essential layer especially in OSCs and PSCs is the interlayer, which consists of the ETL and the HTL. These layers play a pivotal role in enhancing the PCE by facilitate the transport of electron and hole charges towards the electrode while preserving its transparency [33-36]. Typically, ETL and HTL materials are transparent or nearly transparent. While some of these materials may exhibit slight coloration, the thin layer of these materials typically used in solar cells does not significantly affect the overall transparency of the device. Commonly used ETL materials include TiO_2, zinc oxide (ZnO), lithium fluoride (LiF) and tin oxide (SnO_2). For HTLs, materials such as molybdenum oxide (MoO_3), Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), tungsten oxide (WO_3) and Spiro-OMeTAD are frequently employed.

For opaque solar cells, metal materials such as gold (Au), silver (Ag), and aluminum (Al) are commonly used for back electrodes, typically around 100 nm, to ensure high electrical conductivity. In contrast, for STC-SCs, effective transparent and colored back electrodes are crucial, striking the best balance between electrical conductivity and optical transparency. A wide range of materials for transparent back electrodes in devices has been explored, including ultrathin metals, oxide/metal/oxide multilayers, metal/oxide/metal multilayers, metal nanowires, carbon nanotubes, and transparent conducting polymers such as PEDOT:PSS.

3.4 Mechanism of Coloration

One of the primary design approaches for STCSCs is the modulation of color through internal and external modifications. In many internal modifications, the coloration of a solar cell that originates from the photoactive layer is primarily due to the absorption and scattering of light by the materials used in the layer. The photoactive layer is responsible for converting sunlight into electrical energy, and it typically absorbs light in specific wavelengths. The color observed in the solar cell is a result of the wavelengths of light that are not absorbed by the photoactive material but instead are reflected or transmitted.

For instance, in OSC or PSC, the photoactive materials often have a particular bandgap that corresponds to certain parts of the light spectrum. In DSSC, the organic dyes and pigment are responsible for coloration of solar cells. The color of the solar cell may appear depending on which wavelengths of light are absorbed, and which are reflected. If a material absorbs most of the visible spectrum but reflects or transmits light in a certain range, the cell will appear colored according to that range.

Recent studies have focused on external modifications to tune coloration by utilizing advanced materials and structures, such as Fabry-Pérot etalon-type electrodes and distributed bragg reflector. [5,6,37-41] Fabry-Pérot etalon-type electrodes not only function as top conducting layers but also serve as color filters, enabling the production of vivid and saturated colors. Typically, these electrodes consist of a metal oxide cavity layer sandwiched between two thin metal mirrors (Figure 7(a)). Studies shown in Figures 7(b) and 7(c) demonstrate that this structure can achieve transmission rates above 50%. The thickness of the layers is critical in determining which wavelengths of light undergo constructive or destructive interference, thereby enabling the creation of specific colors. Figure 7(b) displays color filters for blue, green, and red, along with their transmission intensities, fabricated using Ag and e-beam evaporated TiO_2. Meanwhile, Figure 7(c) shows color filters for blue, green, orange, and red, with their corresponding transmission intensities, made using Ag and solution-processed TiO_2.

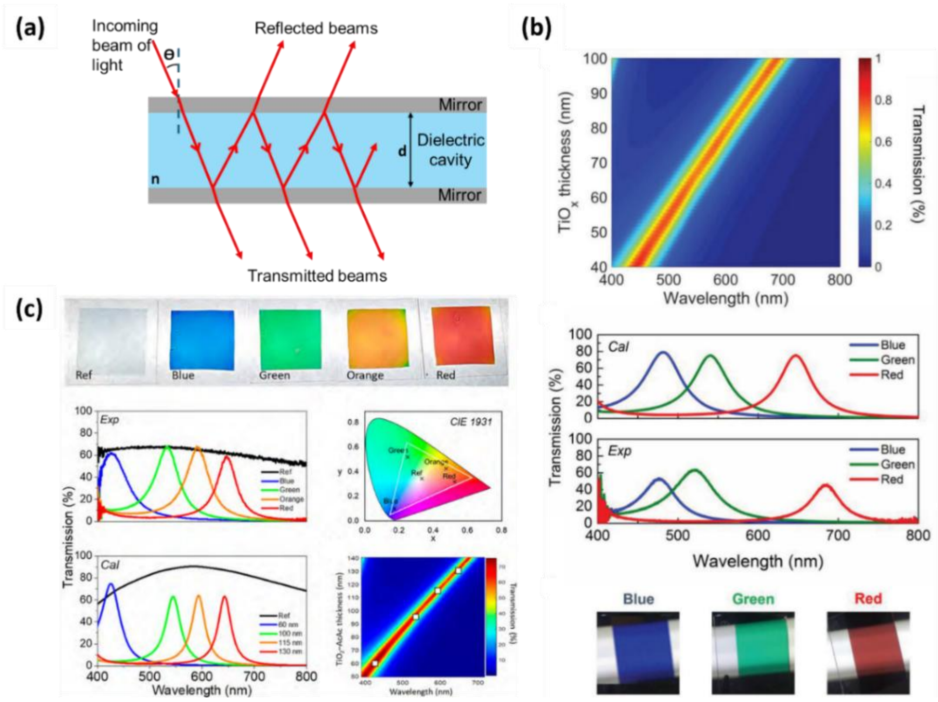

Fig. 7. (a) Schematic diagram of multiple resonance phenomenon in Fabry-Perot resonator (Reproduced under the terms of the CC BY-NC-ND 4.0 license [38] Copyright 2025, Elsevier) (b) Calculated transmission of the colour filter as a function of wavelength and TiO_2 thickness, transmission spectra of blue, green, and red color filters, including calculated and measured data, and images of the fabricated filters (Reproduced with permission from ref [5] Copyright 2018, WILEY-VCH) (c) Photos and transmission spectra of fabricated color filters (blue, green, orange, and red), CIE chromaticities, and calculated transmission of the color filter as a function of wavelength and TiO_2 thickness (Reproduced with permission from ref [6] Copyright 2019, American Chemical Society)

4. Performance of STC-SCs

Table 1 compares STC-SCs with traditional opaque solar cells, highlighting key differences in their architectural applications. STC-SCs offer flexibility in design, allowing for a combination of color and transparency, making them ideal for integration into building facades, windows, and skylights, while still permitting natural light to pass through. In contrast, traditional solar panels are typically opaque, large, and less visually appealing, making them suitable mainly for rooftops or standalone installations. STC-SCs generate power while letting in light, providing a dual function, but their efficiency is generally lower due to the trade-off between light transmission and energy capture. On the other hand, traditional panels are more efficient in energy generation, as they capture more sunlight. While STC-SCs are sustainable and reduce energy consumption, they may have a higher environmental impact during production. Traditional solar cells, with their established manufacturing processes, contribute to sustainability through clean energy generation but are less adaptable for architectural integration.

Table 1
Comparison of STC-SCs with Traditional Solar Cells for Architectural Applications

Feature	STC-SCs	Traditional Solar Cells
Aesthetic Appeal	Flexible design with color and transparency options.	Typically, large and opaque, less visually appealing.
Light Transmission	Allows light to pass through, maintaining natural light.	Blocks all light.
Energy Generation	Generates power while letting light in.	Focuses solely on energy generation.
Structural Compatibility	Can be added to glass or building materials.	Requires separate installation space.
Visual Transparency	Partial visibility, offers privacy and light control.	Completely opaque with no visibility.
Efficiency	Lower efficiency due to light transmission trade-off.	Higher efficiency with more sunlight capture.
Sustainability	Reduces energy use but may have higher manufacturing impact.	Reduces energy use with a more established production process.
Best Applications	Used in windows, facades, and architectural designs.	Used mostly on rooftops or as standalone panels.

Nam, M. et al. [42] developed highly efficient STC-SCs based on quaternary blends (Q-blend), combining two polymer donors, poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-benzo[1,2-b:4,5-b′]dithiophene))-*alt*-(5,5-(1′,3′-di-2-thienyl-5′,7′-bis(2-ethylhexyl)benzo[1′,2′-c:4′,5′-c′]dithiophene-4,8-dione)] (PBDB-T) and poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b;4,5-b′]dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno-[3,4-b]thiophene-)-2-carboxylate-2–6-diyl)] (PTB7-Th), along with two small-molecule acceptors: [6,6]-Phenyl C71 butyric acid methyl ester ($PC_{70}BM$) and 3,9-bis(2-methylene-(3-(1,1-dicyanomethylene)-indanone))-5,5,11,11-tetrakis(5-hexylthienyl)-dithieno[2,3-d:2′,3′-d′]-s-indaceno[1,2-b:5,6-b′]dithiophene (ITIC-Th). The devices employed an inverted structure, with poly[(9,9-bis(3′-(*N*,*N*-dimethylamino)propyl)-2,7-fluorene)-*alt*-2,7-(9,9-dioctylfluorene) (PFN) as the ETL, MoO_3 as the HTL, and ITO and Ag as electrodes (Figure 8(a) and 8(b)). As illustrated in Figure 8(c), the Q-blend exhibited noticeable transparency, with an average visible transmittance (AVT) of 63%, achieved by controlling the thickness of the Ag top electrode to enhance transparency. The STC-SCs were fabricated with a 15-nm thick Ag top electrode. Figure 8(d) shows a photograph of the STC-SCs, where the sculpture in the background is clearly visible through the blue-hued devices. To verify the outstanding performance of the Q-blends, an opaque device with a 100 nm Ag thickness was pre-optimized and achieved a PCE of 9.58%. Meanwhile, the STC-SCs with the 15-nm thick Ag electrode exhibited a PCE of 7.91%. The J_{SC} values derived from the external quantum efficiency (EQE) spectra were consistent with those obtained from current density–voltage (J–V) analysis, as shown in Figures 8(e) and 8(f).

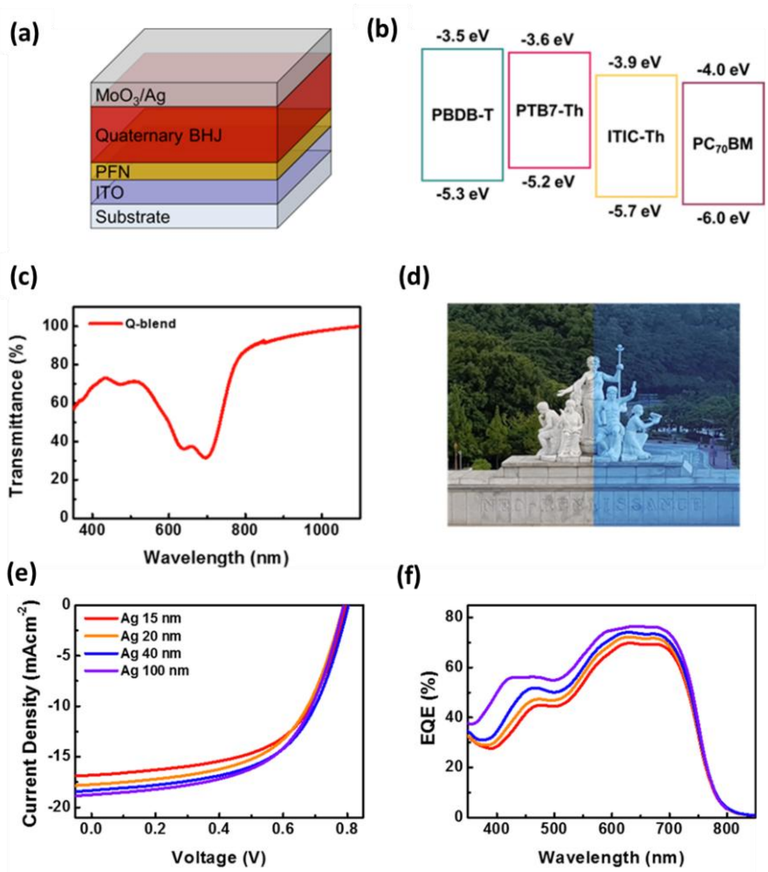

Fig. 8. (a) Schematic diagram (b) energy level of STC-SCs (c) Transmission spectrum of active layer (d) A photograph taken without (left) and with (right) of STC-SCs (e) J-V curve (f) EQE spectra of device with varying Ag top electrode thickness (Reproduced with permission from ref [42] Copyright 2019, Elsevier)

In another study by Sung *et al.,*[43] two different photoactive layers were fabricated: one using Poly[[4,8-bis[5-(2-ethylhexyl)-4-fluoro-2-thienyl]benzo- [1,2-b:4,5-b']dithiophene-2,6-diyl]-2,5-thiophenediyl- [5,7-bis(2-ethylhexyl)-4,8-dioxo-4H,8H-benzo[1,2-c:4,5-c']- dithiophene-1,3-diyl]-2,5-thiophenediyl] (PM6) and 2,2'-((2Z,2'Z)-((12,13-bis(2-ethylhexyl)-3,9-diundecyl-12,13-dihydro-[1,2,5]thiadiazolo[3,4-e]thieno[2'',3'':4',5']thieno[2',3':4,5]pyrrolo[3,2-g]thieno[2',3':4,5]thieno[3,2-b]indole-2,10-diyl)bis(methanylylidene))bis(5,6-difluoro-3-oxo-2,3-dihydro-1H-indene-2,1-diylidene))dimalononitrile (Y6), and the other using (bis(4-(N,N-dimethylamino)phenyl) thieno[3,2-b]thiophene-2,1,3-benzothiadiazole) (DTDCPB) and -Fullerene-C70 (C70) (Figure 9(a) and 9(e)) [5,6]. Both sets of organic materials are recent high-efficiency materials with promising PCE. The structure for the PM6 and Y6 materials consists of an inverted configuration with ZnO and PEIE as the ETL, MoO_3 as the HTL, and ITO and Ag as electrodes (Figure 9(b)). In contrast, for DTDCPB and C70, a conventional structure was used, with MoO_3 as HTL and Bathocuproine (BCP) as ETL (Figure 9(f)). In both cases, a color filter was incorporated into the devices to impart color,[5,6,38,39] consisting of Ag/ Dipyrazino[2,3-f:2',3'-h]quinoxaline-2,3,6,7,10,11-hexacarbonitrile (HATCN)/Ag layers. Based on the J-V curves and EQE spectra shown in Figures 9(c) and 9(g), the semitransparent device with PM6 and Y6 photoactive materials achieved a PCE of 12.63%, while the STC-SCs for blue, green, and red exhibited PCEs of 13.28%, 12.90%, and 12.94%, respectively. For DTDCPB and C70, the semitransparent device achieved a PCE of 7.25%, with STC-SCs for blue, green, and red yielding PCEs of 7.42%, 7.52%, and 7.36%, respectively. As shown in Figures 9(d) and 9(h), the STC-SCs exhibited bright and vivid hues of blue, green, and red, enhancing the visual appeal of the devices.

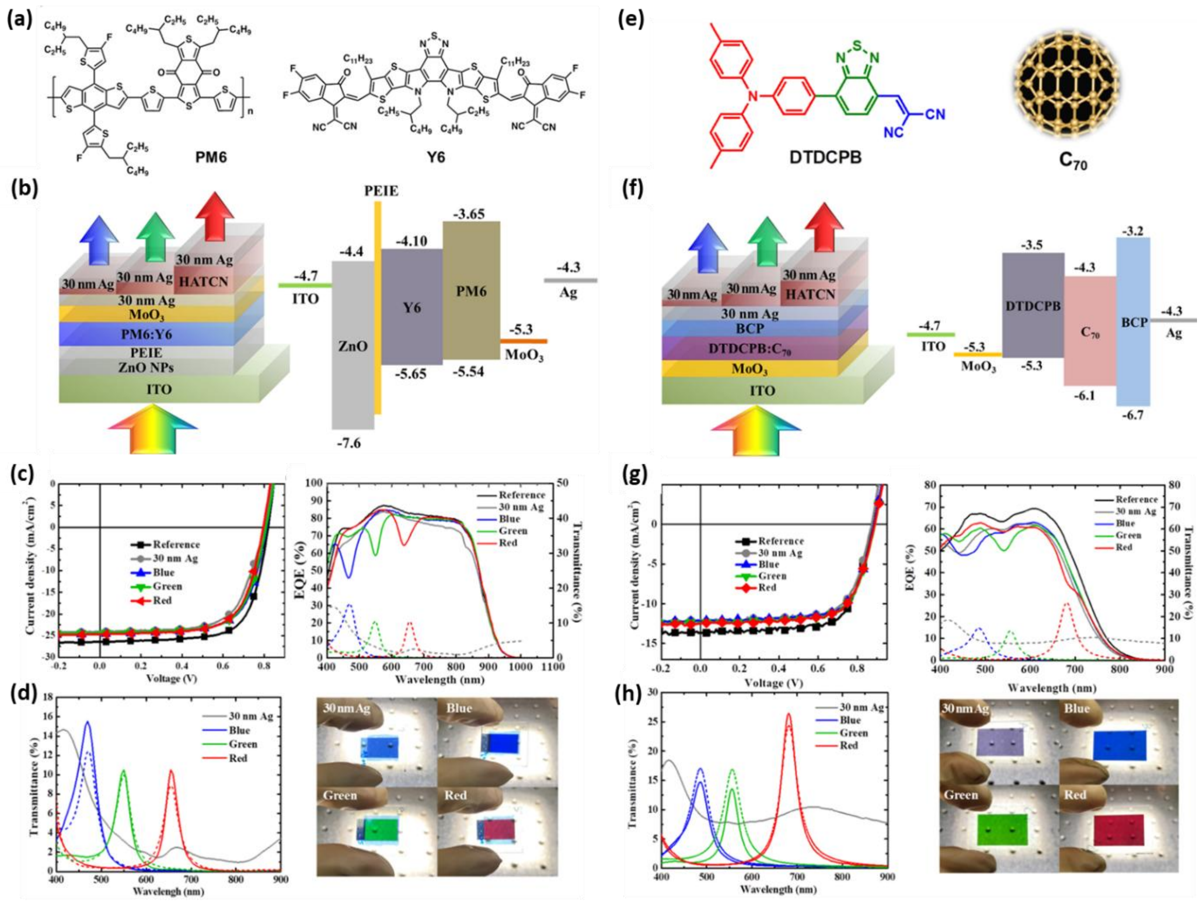

Fig 9. (a) Schematic diagram (b) energy level of STC-SCs (c) Transmission spectrum of active layer (d) A photograph taken without (left) and with (right) of STC-SCs (e) J-V curve (f) EQE spectra of device with varying Ag top electrode thickness (Reproduced with permission from ref [43] Copyright 2021, Elsevier)

Upama *et al.,* [44] investigate the perovskite photoactive layer and fabricate STC-SCs for use in BIPV. In comparison with other devices reported by different researchers, their use of MoO_3/Ag/MoO_3 electrodes results in an efficiency greater than 9% (Figure 10(a)). The device structure comprises $PC_{71}BM$ as the ETL, Spiro-OMeTAD as the HTL, and ITO and MoO_3/Ag/MoO_3 layers as transparent electrodes (Figures 10(b) and 10(c)). As the thickness of the $MAPbI_3$ layer decreases, the device's transmittance increases (Figure 10(d)). Figures 10(e) and 10(f) display the PCE, AVT, and real images of the devices. The best-performing device achieved 9.23% efficiency at 12.4% AVT with a perovskite layer thickness of 93 nm. By further reducing the perovskite layer thickness, transparency increased to 20.5%, but the efficiency dropped to 3.5%.

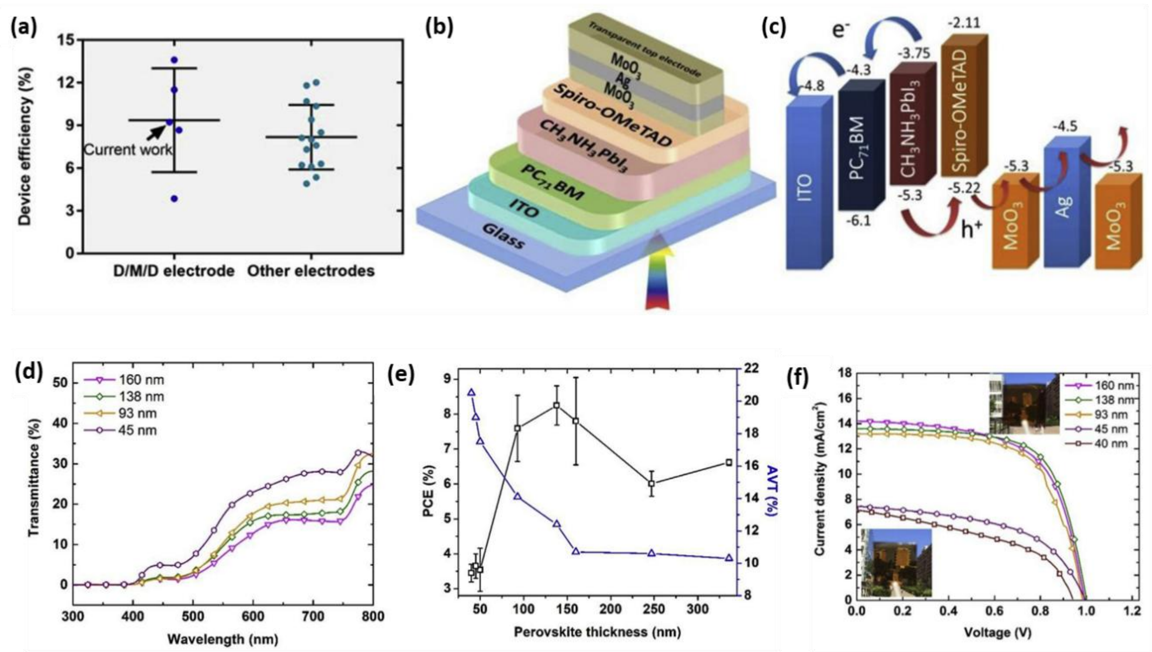

Fig. 10. (a) Comparison of device efficiency of STC-SCs with various electrodes (b) Schematic diagram (c) energy level of STC-SCs (d) UV-Vis transmittance (e) device efficiency and AVT (f) J-V curves of STC-SCs with different thickness of perovskite film (Reproduced with permission from ref [44] Copyright 2019, Elsevier)

Another study by Chen *et al.,* [45] employed a planar p-i-n perovskite solar cell structure (ITO/PEDOT:PSS/PVK/PCBM/Ag/PCBM/Ag) synthesized with precursor concentrations ranging from 0.75 M to 1.75 M, exploring their potential for BIPV systems (Figure 11(a)). The selective color gamut for Fabry-Perot electrodes was simulated with varying thicknesses of n-type PCBM and p-type PEDOT:PSS, resulting in blue, cyan, green, and purple color films (Figure 11(b)). Figure 11(c) displays the J-V characteristic curves and and Scanning Electron Microscope (SEM) image of the translucent perovskite structure with precursor concentrations ranging from 0.75 M to 1.75 M. A peak PCE of 6.07% was achieved with a 1.5 M precursor concentration. The results revealed that surface coverage increased from 48.91% to 54.47% as the precursor concentration rose from 0.75 M to 1.5 M, but decreased to 47.05% when the concentration reached 1.75 M. Figure 11(d) presents the J-V characteristic curves of selective color perovskite solar cells with Ag electrodes and varying PCBM thicknesses (57, 65, and 143 nm), along with the Fabry-Perot cavity, red-colored perovskite solar cells with an n-type PCBM Fabry-Perot cavity, and hydrolysis images of PEDOT:PSS spun on $CH_3NH_3PbI_3$.

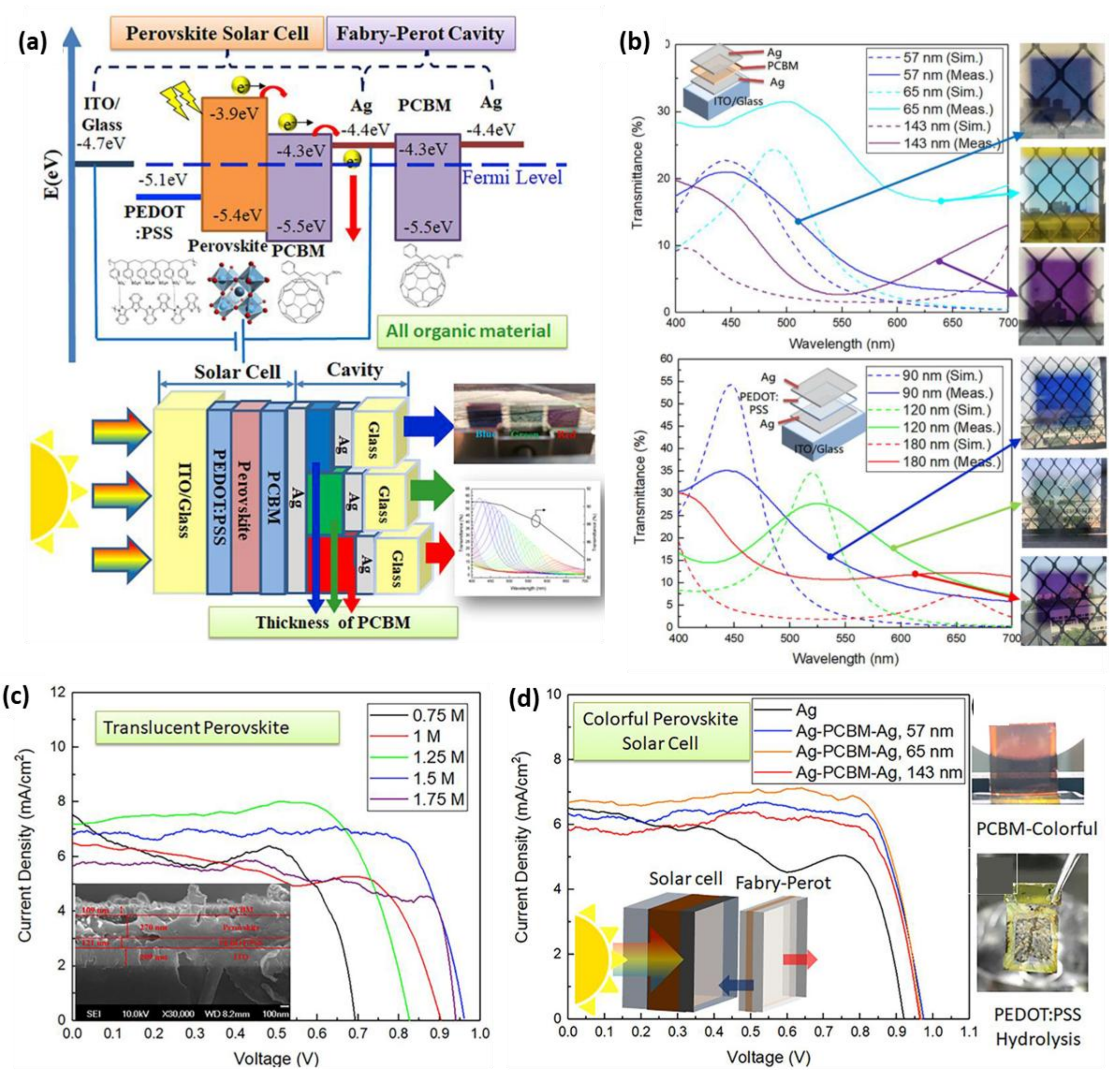

Fig. 11. (a) Schematic diagram illustrating the energy gap matching of the ITO/PEDOT:PSS/PVK/PCBM/Ag/PCBM/Ag solar cell, along with the structure of the selective color perovskite solar cell (b) Transmittance and spectra from simulations and measurements of the (top) PCBM cavity material with thicknesses of 57, 65, and 143 nm, and (bottom) PEDOT:PSS cavity material with thicknesses of 90, 120, and 180 nm (c) J–V characteristic curves and SEM images of translucent perovskite (d) J-V characteristic curves of selective color perovskite solar cells deposited with Ag electrodes and varying PCBM thicknesses (57, 65, and 143 nm) for the Fabry-Perot cavity, red-colored perovskite solar cells with an n-type PCBM Fabry-Perot cavity, and a hydrolysis image of PEDOT:PSS spun on CH3NH3PbI3 (Reproduced with permission from ref [45] Copyright 2021, Elsevier)

5. Research Gaps and Challenges in STC-SCs

While STC-SCs offer significant promise in enhancing energy efficiency and aesthetics, there are still a gap and challenges hinder their widespread use in architectural applications.

5.1 Low PCE

STC-SCs generally exhibit lower efficiency compared to traditional opaque solar cells due to the inherent trade-off between transparency and energy absorption. This issue is particularly amplified in indoor applications, where light intensity is significantly lower than outdoor sunlight. Research into novel materials or technologies that can improve the energy conversion efficiency without compromising transparency or color could help overcome this limitation.

5.2 Material Stability and Durability

Material stability and durability also remain critical concerns for the long-term viability of STC-SCs. While materials like organic photovoltaics and perovskites offer promising properties, they are susceptible to degradation from environmental factors such as moisture, UV exposure, and temperature fluctuations. This reduces their lifespan and efficiency, particularly in architectural settings where the cells are exposed to varying weather conditions. Developing more robust materials and protective coatings to enhance the durability of STC-SCs is essential, but it adds complexity and cost to the technology, which needs to be addressed through further material engineering.

5.3 Integration with Existing Building

Integration with existing building structures presents significant challenges, especially for older or non-standard buildings. Designing STC-SCs that can be seamlessly incorporated into windows, facades, or skylights, while maintaining both aesthetic and functional value, is not straightforward. The integration process can be complicated by issues such as non-standard building dimensions and the need for compatibility with various architectural styles. Additionally, the process of retrofitting buildings with STC-SCs needs to be simplified to ensure practical installation without compromising the building's integrity or visual appeal.

5.4 Sustainability Assessments

Sustainability assessments are another critical research gap. A comprehensive lifecycle analysis comparing the environmental impact of STC-SCs to conventional solar panels is needed to assess their true sustainability. Such studies would evaluate not only the energy savings during the operational life of STC-SCs but also their environmental footprint during production and disposal. Furthermore, scalability and cost remain a significant barrier to widespread adoption. The manufacturing process for STC-SCs is more complex, and the cost is higher compared to traditional solar panels. Research into reducing production costs, improving manufacturing efficiency, and scaling up the technology for broader architectural integration is essential for making STC-SCs a mainstream option.

6. Future Directions in STC-SCs

The future of STC-SCs in architectural design holds great promise, enhancing energy efficiency, versatility, and aesthetic appeal. With the rising demand for sustainable building materials, STC-SCs offer a unique solution by integrating renewable energy while preserving natural light.

6.1 Advances in Materials and Efficiency

Improving material PCE focuses on synthesizing substances that absorb longer near-infrared wavelengths, enhancing sunlight absorption and transparency by reducing visible light absorption. Incorporating quantum dots and nanomaterials further optimizes energy harvesting for greater efficiency [46]. The use of ultrathin hybrid-metal electrodes and fine-tuned dielectric mirrors also can help in tuning the colour with efficiencies comparable to their opaque counterparts [47].

6.2 Integration with Smart Technology

STC-SCs are increasingly integrated with smart technologies, such as electrochromic or photochromic properties, enabling windows to adjust transparency and color based on light, temperature, or user preference. This capability promotes energy-efficient smart windows that regulate light and temperature.

6.3 Flexible and Lightweight Designs

The development of flexible, lightweight solar cells enables integration into non-traditional surfaces like furniture, wall panels, and portable devices [48]. This adaptability allows for easy retrofitting of buildings and transforms everyday surfaces into energy generators, promoting sustainability indoors.

7. Conclusions

In conclusion, STC-SCs represent a significant advancement in solar technology, offering a unique combination of energy generation and aesthetic flexibility for architecture applications. Their ability to allow light to pass through while generating renewable energy makes them ideal for integration into building facades, windows, and interior spaces, supporting the growing demand for energy-efficient and sustainable buildings. The potential to customize transparency and color further enhances their appeal, enabling architects to incorporate them seamlessly into modern designs without compromising visual appeal. While challenges such as lower PCE remain, ongoing advancements in materials like new synthesized perovskites and organic materials are steadily improving the performance of these cells. As manufacturing techniques evolve and costs decrease, STC-SCs will become increasingly accessible, transforming the way we design and power indoor spaces. Ultimately, these solar cells have the potential to play a pivotal role in creating greener, more energy-efficient buildings in the future.

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References

[1] Chae, Young Tae, Jeehwan Kim, Hongsik Park, and Byungha Shin. "Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells." *Applied Energy* 129 (2014): 217-227. https://doi.org/10.1016/j.apenergy.2014.04.106

[2] Li, Benxuan, Bo Hou, and Gehan AJ Amaratunga. "Indoor photovoltaics, The Next Big Trend in solution-processed solar cells." *InfoMat* 3, no. 5 (2021): 445-459. https://doi.org/10.1002/inf2.12180

[3] You, Young-Jun, Muhammad Ahsan Saeed, Shafidah Shafian, Jisoo Kim, Sang Hyeon Kim, Sung Hyeon Kim, Kyungkon Kim, and Jae Won Shim. "Energy recycling under ambient illumination for internet-of-things using metal/oxide/metal-based colorful organic photovoltaics." *Nanotechnology* 32, no. 46 (2021): 465401. https://doi.org/10.1088/1361-6528/ac13e7
[4] Yan, Bin, Xinsheng Liu, Wenbo Lu, Mingjie Feng, Hui-Juan Yan, Zongbao Li, Shunchang Liu, Cong Wang, Jin-Song Hu, and Ding-Jiang Xue. "Indoor photovoltaics awaken the world's first solar cells." *Science Advances* 8, no. 49 (2022): eadc9923. https://doi.org/10.1126/sciadv.adc9923
[5] Kim, Youngji, Jieun Son, Shafidah Shafian, Kyungkon Kim, and Jerome K. Hyun. "Semitransparent blue, green, and red organic solar cells using color filtering electrodes." *Advanced Optical Materials* 6, no. 13 (2018): 1800051. https://doi.org/10.1002/adom.201800051
[6] Shafian, Shafidah, Jieun Son, Youngji Kim, Jerome K. Hyun, and Kyungkon Kim. "Active-material-independent color-tunable semitransparent organic solar cells." *ACS Applied Materials & Interfaces* 11, no. 21 (2019): 18887-18895. https://doi.org/10.1021/acsami.9b03254
[7] Wang, Hao, Herlina Arianita Dewi, Teck Ming Koh, Annalisa Bruno, Subodh Mhaisalkar, and Nripan Mathews. "Bifacial, color-tunable semitransparent perovskite solar cells for building-integrated photovoltaics." *ACS applied materials & interfaces* 12, no. 1 (2019): 484-493. https://doi.org/10.1021/acsami.9b15488
[8] Khandelwal, Kanupriya, Subhayan Biswas, and Ganesh D. Sharma. "Advancing multifunctional semitransparent organic solar cells through strategic optical layer integration." *ACS Applied Energy Materials* 7, no. 16 (2024): 7085-7095. https://doi.org/10.1021/acsaem.4c01493
[9] Barraud, Emmanuel. "Stained glass solar windows for the swiss tech convention center." *Chimia* 67, no. 3 (2013): 181-182. https://doi.org/10.2533/chimia.2013.181
[10] "Dye Solar Cell Façade at SwissTech Convention Center at EPFL, by Solaronix," *Juan Bisquert's Blog*, April 8, 2014.
[11] Herzog, A. *Epfl's campus has the world's first solar window*. 2005.
[12] Spencer Allan, "University of Washington Life Sciences Building," *Perkins&Will*, October 24, 2023.
[13] 舒岳康, "Life Sciences Building for the University of Washington / Perkins+Will," *ArchDaily*, November 27, 2024.
[14] SMA Solar Technology AG, *Solar Energy and Architecture with SUNNY BOY 2000: Berlin Central Station Reference Project*, (Niestetal, Germany: SMA Solar Technology AG, 2006).
[15] Darren Ang, "GuocoLand Unveils Urban Park at Tanjong Pagar Centre with Series of Events," *Darren Bloggie - Singapore Lifestyle Blog*, October 29, 2017.
[16] "Prof. Stefan Rahmstorf on X: 'How Often Have I Changed Trains at Berlin Central Station? Can You See the Semi-Transparent PV Cells on Its Glass Roof? Https://T.Co/OHb4EcZMJJ' / X," *X (Formerly Twitter)*, n.d.
[17] MIT Energy Initiative, "Transparent Solar Cells," *Main*, March 29, 2024.
[18] Shin, Dong Hee, Chan Wook Jang, Ha Seung Lee, Sang Woo Seo, and Suk-Ho Choi. "Semitransparent flexible organic solar cells employing doped-graphene layers as anode and cathode electrodes." *ACS applied materials & interfaces* 10, no. 4 (2018): 3596-3601. https://doi.org/10.1021/acsami.7b16730
[19] Kawashima, Takuya, Hiroshi Matsui, and Nobuo Tanabe. "New transparent conductive films: FTO coated ITO." *Thin Solid Films* 445, no. 2 (2003): 241-244. https://doi.org/10.1016/S0040-6090(03)01169-6
[20] Kang, Myung-Gyu, Ting Xu, Hui Joon Park, Xiangang Luo, and L. Jay Guo. "Efficiency enhancement of organic solar cells using transparent plasmonic Ag nanowire electrodes." (2010). https://doi.org/10.1002/adma.201001395
[21] Author, Best Research-Cell Efficiencies, (2025) https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf
[22] Shafian, Shafidah, Fitri Norizatie Mohd Salehin, Sojeong Lee, Azlan Ismail, Shuhaida Mohamed Shuhidan, Lin Xie, and Kyungkon Kim. "Development of Organic Semiconductor Materials for Organic Solar Cells via the Integration of Computational Quantum Chemistry and AI-Powered Machine Learning." *ACS Applied Energy Materials* 8, no. 2 (2025):699-722. https://doi.org/10.1021/acsaem.4c02937
[23] Hong, Minjeong, Jiyae Youn, Ka Yeon Ryu, Shafidah Shafian, and Kyungkon Kim. "Improving the Stability of Non-fullerene-Based Organic Photovoltaics through Sequential Deposition and Utilization of a Quasi-orthogonal Solvent." *ACS Applied Materials & Interfaces* 15, no. 16 (2023): 20151-20158. https://doi.org/10.1021/acsami.3c02071
[24] Kim, Hyunkyoung, Ye-Jin Kong, Won-Suk Kim, Shafidah Shafian, and Kyungkon Kim. "Enhancing Reproducibility in Organic Solar Cell Fabrication via Static Sequential Deposition with Cross-Linked Polymer Donor and Nonfullerene Acceptor." *ACS Applied Polymer Materials* 6, no. 10 (2024): 5814-5821. https://doi.org/10.1021/acsapm.4c00477
[25] Kim, Hyunkyoung, Yuchan Heo, Yeji Na, Shafidah Shafian, BongSoo Kim, and Kyungkon Kim. "Cross-Linking-Integrated Sequential Deposition: A Method for Efficient and Reproducible Bulk Heterojunctions in Organic Solar Cells." *ACS Applied Materials & Interfaces* 16, no. 41 (2024): 55873-55880. https://doi.org/10.1021/acsami.4c13237

[26] Hwang, Heewon, Hoyeon Lee, Shafidah Shafian, Wooseop Lee, Jeesoo Seok, Ka Yeon Ryu, Du Yeol Ryu, and Kyungkon Kim. "Thermally stable bulk heterojunction prepared by sequential deposition of nanostructured polymer and fullerene." *Polymers* 9, no. 9 (2017): 456. https://doi.org/10.3390/polym9090456

[27] Zhang, Xiao, Linqing Wang, Shafidah Shafian, Peng Wang, Yuping Zhao, Pengcheng Wang, Bin Wu et al. "Crosslinking-Driven Chemical Homogeneity Enhances Performance of Pre-Seeded Perovskite Solar Cells." *Small* 21, no. 6 (2025): 2408362. https://doi.org/10.1002/smll.202408362

[28] Qi, Shuwen, Chenghao Ge, Peng Wang, Bin Wu, Yuping Zhao, Rongjun Zhao, Shafidah Shafian, Yong Hua, and Lin Xie. "Improving Perovskite Solar Cell Performance and Stability via Thermal Imprinting-Assisted Ion Exchange Passivation." *ACS Applied Materials & Interfaces* 16, no. 38 (2024): 51037-51045. https://doi.org/10.1021/acsami.4c08538

[29] Grätzel, Michael. "Dye-sensitized solar cells." *Journal of photochemistry and photobiology C: Photochemistry Reviews* 4, no. 2 (2003): 145-153. https://doi.org/10.1016/S1389-5567(03)00026-1

[30] Hagfeldt, Anders, Gerrit Boschloo, Licheng Sun, Lars Kloo, and Henrik Pettersson. "Dye-sensitized solar cells." *Chemical reviews* 110, no. 11 (2010): 6595-6663. https://doi.org/10.1021/cr900356p

[31] Karuthedath, Safakath, Julien Gorenflot, Yuliar Firdaus, Neha Chaturvedi, Catherine SP De Castro, George T. Harrison, Jafar I. Khan et al. "Intrinsic efficiency limits in low-bandgap non-fullerene acceptor organic solar cells." *Nature Materials* 20, no. 3 (2021): 378-384. https://doi.org/10.1038/s41563-020-00835-x

[32] Tao, Shuxia, Ines Schmidt, Geert Brocks, Junke Jiang, Ionut Tranca, Klaus Meerholz, and Selina Olthof. "Absolute energy level positions in tin-and lead-based halide perovskites." *Nature communications* 10, no. 1 (2019): 2560. https://doi.org/10.1038/s41467-019-10468-7

[33] Shafian, Shafidah, Heewon Hwang, and Kyungkon Kim. "Near infrared organic photodetector utilizing a double electron blocking layer." *Optics Express* 24, no. 22 (2016): 25308-25316. https://doi.org/10.1364/OE.24.025308

[34] Ryu, Ka Yeon, Shafidah Shafian, Jongchan Shin, Yu Jin Lee, Minjae Lee, and Kyungkon Kim. "Linear polyurethane ionenes for stable interlayer of organic photovoltaics." *Journal of Power Sources* 542 (2022): 231772. https://doi.org/10.1016/j.jpowsour.2022.231772

[35] Shin, Solbi, Shafidah Shafian, Ka Yeon Ryu, Young-Kyo Jeon, Won-Suk Kim, and Kyungkon Kim. "Solution-Processed TiO_2 Nanoparticles Functionalized with Catechol Derivatives as Electron Transporting Layer Materials for Organic Photovoltaics." *Advanced Materials Interfaces* 9, no. 14 (2022): 2200118. https://doi.org/10.1002/admi.202200118

[36] Wang, Peng, Shafidah Shafian, Feng Qiu, Xiao Zhang, Yuping Zhao, Bin Wu, Kyungkon Kim, Yong Hua, and Lin Xie. "Improving redox reactions of Spiro-OMeTAD via p-type molecular scaffold to reduce energy loss at Ag-electrode in perovskite solar cells." *Journal of Energy Chemistry* 102 (2025): 151-160. https://doi.org/10.1016/j.jechem.2024.10.027

[37] Shafian, Shafidah, and Kyungkon Kim. "Panchromatically responsive organic photodiodes utilizing a noninvasive narrowband color electrode." *ACS Applied Materials & Interfaces* 12, no. 47 (2020): 53012-53020. https://doi.org/10.1021/acsami.0c17183

[38] Mohd Salehin, Fitri Norizatie, Puvaneswaran Chelvanathan, Adamu Ahmed Goje, Norasikin Ahmad Ludin, Mohd Adib Ibrahim, and Shafidah Shafian. "Design of blue, green and red colorful semitransparent films using $Ag/SnO_2/Ag$ color filter for integrated into solar cells." *Results in Physics* 70 (2025): 108172. https://doi.org/10.1016/j.rinp.2025.108172

[39] Kim, Bo Youn, Shafidah Shafian, and Kyungkon Kim. "High-Performance Semitransparent Color Organic Photodiodes Enabled by Integrating Fabry–Perot and Solution-Processed Distributed Bragg Reflectors." *Advanced Materials Interfaces* 10, no. 31 (2023): 2300421. https://doi.org/10.1002/admi.202300421

[40] Park, Suhyeon, Shafidah Shafian, Juhwan Lee, Seungyun Jo, Seungbae Jeon, Seungjae Lee, Ding Shangxian, Hyungju Ahn, Kyungkon Kim, and Du Yeol Ryu. "High-Efficiency Structural Coloration Enabled by Defect-Free Block Copolymer Self-Assembly for a Solar Cell Distributed Bragg Reflector." *Advanced Optical Materials* 11, no. 24 (2023): 2301357. https://doi.org/10.1002/adom.202301357

[41] Shafian, Shafidah, Ga Eun Lee, Hyeonggeun Yu, Jeung-hyun Jeong, and Kyungkon Kim. "High-Efficiency Vivid Color CIGS Solar Cell Employing Nondestructive Structural Coloration." *Solar RRL* 6, no. 4 (2022): 2100965. https://doi.org/10.1002/solr.202100965

[42] Nam, Minwoo, Hye Yeon Noh, Joo-Han Kang, Junhee Cho, Byoung Koun Min, Jae Won Shim, and Doo-Hyun Ko. "Semi-transparent quaternary organic blends for advanced photovoltaic applications." *Nano Energy* 58 (2019): 652-659. https://doi.org/10.1016/j.nanoen.2019.01.090

[43] Sung, Yun-Ming, Meng-Zhen Li, Dian Luo, Yan-De Li, Sajal Biring, Yu-Ching Huang, Chun-Kai Wang, Shun-Wei Liu, and Ken-Tseng Wong. "A micro-cavity forming electrode with high thermal stability for semi-transparent colorful

organic photovoltaics exceeding 13% power conversion efficiency." *Nano Energy* 80 (2021): 105565. https://doi.org/10.1016/j.nanoen.2020.105565

[44] Upama, Mushfika Baishakhi, Md Arafat Mahmud, Haimang Yi, Naveen Kumar Elumalai, Gavin Conibeer, Dian Wang, Cheng Xu, and Ashraf Uddin. "Low-temperature processed efficient and colourful semitransparent perovskite solar cells for building integration and tandem applications." *Organic electronics* 65 (2019): 401-411. https://doi.org/10.1016/j.orgel.2018.11.037

[45] Chen, Hsi-Chao, Ya-Jun Zheng, and Shu-Wei Guo. "Solution process of selective color-gamut perovskite solar cell modulated with organic Fabry-Perot electrode for building-integrated photovoltaic." *Solar Energy Materials and Solar Cells* 230 (2021): 111192. https://doi.org/10.1016/j.solmat.2021.111192

[46] De Chen, Jing, Hui-Min Liu, Hao Ren, Ye-Fan Zhang, Hong-Yi Hou, Yan-Qing Li, Zisheng Su, and Jian-Xin Tang. "Semitransparent Organic Solar Cells with Viewing-Angle-Independent Janus Structural Colors." *Advanced Optical Materials* 11, no. 1 (2023): 2201848. https://doi.org/10.1002/adom.202201848

[47] Xu, Guiying, Liang Shen, Chaohua Cui, Shanpeng Wen, Rongming Xue, Weijie Chen, Haiyang Chen et al. "High-performance colorful semitransparent polymer solar cells with ultrathin hybrid-metal electrodes and fine-tuned dielectric mirrors." *Advanced Functional Materials* 27, no. 15 (2017): 1605908. https://doi.org/10.1002/adfm.201605908

[48] Han, Danao, Shuo Han, Ziming Bu, Yanyu Deng, Chunyu Liu, and Wenbin Guo. "Flexible color tunability and high transmittance semitransparent organic solar cells." *Solar RRL* 6, no. 9 (2022): 2200441. https://doi.org/10.1002/solr.202200441