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Analysis of Commercialization Potential of Transparent Photovoltaics in the Context of Carbon Neutrality

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Abstract

The increasing global industrialization and over-exploitation of fossil fuels has led to the release of greenhouse gases, resulting in higher global temperatures and environmental problems. As a result, there is a growing demand for renewable energy in order to achieve net zero carbon emissions. Building-integrated photovoltaics (BIPVs) can replace building structures, such as roofs or walls. Among others, transparent photovoltaics (TPVs), which combine visible light transparency and solar energy conversion, are being developed to complement BIPVs for applications such as windows in buildings or vehicles. In this paper, we collate the latest advances in TPVs and strategies for achieving conventional PVs transparency, including thin-film technology, selective light transmission technology and luminescent solar concentrator technology. We further discuss possible research directions for the commercialization of TPVs.

Keywords: Transparent photovoltaics; organic photovoltaics; perovskite solar cells; crystalline silicon solar cells; luminous concentrator solar cells.

1. Introduction

Global climate change is already having a clear impact on the environment.(F. Wang et al., 2021) In response to rising global greenhouse gas concentrations and temperatures, on 12 December 2015, 197 member countries of the United Nations Framework Convention on Climate Change (UNFCCC) agreed at the Paris Climate Change Conference (PCCC) to adopt the Paris Agreement, which sets out a global action plan to combat climate change after 2020. Under the Paris Agreement, each country agreed to limit global temperature increases to less than 2°C and to work towards limiting global temperature increases to less than 1.5°C (2015 agreement). As of February 2021, 124 countries/regions worldwide have declared their intention to be carbon neutral and achieve net zero carbon emissions by 2050 or 2060 (Chen, 2021). In order to achieve the targets set out in the Paris Agreement and to support sustainable development, it is important not only to reduce CO_2 emissions but also to remove CO_2 to achieve net zero or negative carbon emissions from the atmosphere through various social, economic, environmental and technological measures. 135 GW of photovoltaic modules were produced in 2020 (95% of the total for 2020). Crystalline silicon solar cells dominate the world PVs market due to their highly power conversion efficiency (PCE), high stability and low cost, and silicon-based PV solar is expected to be one of the main sources of power generation by 2050.

Due to the increase in urban population and the amount of time people spend in buildings, buildings and cities contribute to the large carbon emissions that contribute to climate change. For cities, one strategy to adapt to climate change is to develop resilient designs that can withstand natural hazards while minimizing the impact on the natural environment (Chen, 2021). In addition, mitigation can be achieved by deploying decentralized energy systems for cities; however, this option has a high initial cost. Buildings can achieve a carbon-free future by utilizing improved building envelopes, renewable materials and 3D printing. In addition, this can be achieved by developing heating and cooling systems powered by renewable energy and using energy efficient technologies (Fawzy, Osman, Doran, & Rooney, 2020). In addition, the use of sensors to monitor and regulate intelligent building equipment such as lighting, and the development of electrical and thermal energy storage systems are promising approaches. In addition, the electromechanical equipment in buildings should be eco-labelled and minimum standards for heating, ventilation and air conditioning systems should be implemented.

Rooftop solar installations in cities, often on high-rise buildings competing with concepts such as green or cool roofs and infrastructure related to heating, cooling and air handling (Y. P. Wang, Tian, Ren, Zhu, & Wang, 2006). In order to increase solar energy production in urban centers, either the amount of electricity generated per unit area needs to be increased, or the collection area needs to be increased by using the building envelope for solar power generation. Due to the predominant use of glass as a building material, the conversion of this building envelope into a power generation source will allow for local energy harvesting and use. In addition to generating electricity, the solarization of window glazing can also provide energy savings through heat dissipation while providing visual comfort. BIPV includes solar panels mounted on the roof and facade, as well as solar windows, forming an overall strategy to achieve a zero energy, zero carbon building. In the current BIPVs market, crystalline silicon (c-Si) PV still leads and dominates the global market, with a market penetration of over 70% in the overall market segment (including roof and façade applications), which remains the trend in the BIPVs market for several years, mainly due to the predictable decline in crystalline silicon cell prices.

With the current market demand shifting towards smart technology for near-zero energy buildings, an increase in demand for building photovoltaics can be foreseen and solar cells are expected to be developed directly on the structure of the building. Evolving thin-film technologies such as copper indium gallium selenide (CIGS), copper zinc tin sulphide (CZTS), organic photovoltaics (OPV) and perovskite solar cells (PSC) are well compatible with such customizable building modules. So far, all semitransparent photovoltaics based on thin-film technology have not yet offered high PCE (>15% at module level), as well as transparency (>20%), stability (ideally >20 years) and color tunability (across the visible spectrum). It is conceivable that in future urban planning the development of commercial high-rise building surfaces in fast growing cities and residential units represent a huge potential for transforming the built environment into a decentralized generator, unlocking the solar potential of unused vertical and horizontal building surfaces and promoting self-consumption through on-site energy production (Figure 1). This paper explores the commercialization potential of several mainstream transparent photovoltaics.

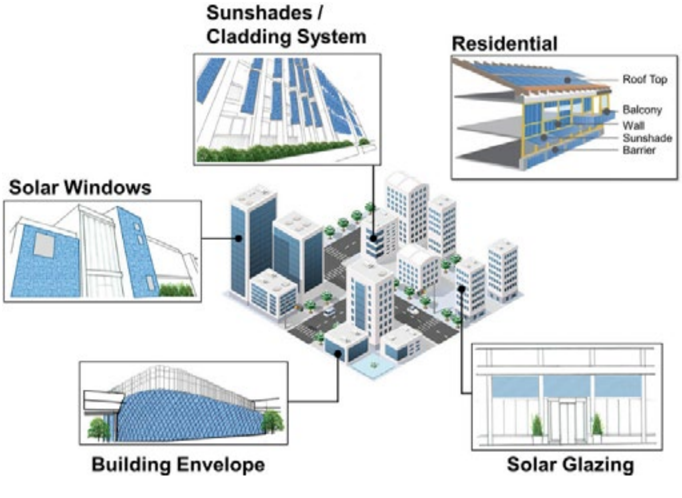

Figure 1

Building-integrated photovoltaics (BIPVs) may include solar cells mounted on roof tops, skylights, balustrades, and façade.

2. Transparent PVs technology classification

In this article we have compiled the latest advances in transparent photovoltaics, including thin film technology, selective light transmission technology and luminescent solar concentrator technology.

3. Thin film technology

BIPVs are connected to commercial and residential homes to enable solar energy harvesting. Although conventional silicon solar cells dominate the current market, second and third generation thin film solar cells based on amorphous silicon, CdTe, CIGS, perovskite or organic photovoltaics (OPVs) are usually regarded as substitutes for BIPVs applications because of their significantly lower costs compared to silicon solar cells. The potential applications of organic and chalcogenide photovoltaics in BIPVs are highlighted.

In recent years, the rapid development of OPVs has achieved PCE of over 19%.(Zhu et al., 2022) At the same time, OPVs show great advantages in terms of light weight, ease of manufacture, low cost and environmental friendliness compared to conventional silicon solar cells. By choosing the right organic material, photon capture in the near infrared (NIR) range and transmission in the visible range can be well optimized to meet the requirements of window and greenhouse applications and to collect photons sufficiently in the NIR range to maintain a high PCE. With the construction and operation of buildings currently accounting for one-fifth of global carbon emissions, it has become crucial to develop innovative technologies to improve the energy efficiency of buildings. Considering that there are over 100 billion square meters of window glass in buildings, replacing ordinary glass with transparent power-generating windows has energy-saving features (Zhou et al., 2019), in addition to energy-saving methods such as low-e glass and thin films. Li et al. developed high-performance transparent power generation windows with excellent power generation and light transmission properties for multifunctional semitransparent organic photovoltaics (ST-OPVs) with excellent optical and photovoltaic properties in the visible to infrared range of the solar spectrum, along with an AVT of 32%, a color rendering index of 90, a near-infrared reflectance of 0.90 and a power conversion efficiency of over 11%. More importantly, large area modules with manufacturing feasibility were successfully obtained with an energy conversion efficiency of 16.04% for opaque (certified at 15.46%) and 11.28% for transparent modules, reaching a new efficiency record for current organic solar modules.(D. Wang et al., 2022) The best current ST-OPVs devices have light utilization efficiency (LUE = PCE * AVT) to 5.35%.(Liu, Zhong, Zhu, Yu, & Li, 2022) In addition to generating window references, the use of ST-OPVs on greenhouse structures offers the opportunity to offset the greenhouse energy demand and also maintain the light requirements of plants. ST-OPVs are particularly promising for greenhouse integration, with attributes such as spectrally tunable transparency and compatibility with thin film flexible profiles for simple module integration.(Emmott et al., 2015) Ravishankar et al. developed a detailed greenhouse system model that combines detailed accounting of the greenhouse environment (temperature, humidity, lighting) with a functional plant growth model, solar power generation from ST-OPVs and system economics. This holistic model allows an assessment of how adding ST-OPVs to greenhouses may be part of a more sustainable solution for the agricultural food industry.(Ravishankar et al., 2022)

Perovskite solar cells (PSCs) have attracted much attention for their low cost and high energy conversion efficiency. In 2009, Miyasaka and his colleagues first reported the use of organic-inorganic lead halide perovskite semiconductors as active light absorbers in solar cells. In this ground-breaking work, the best performing device produced a power conversion efficiency (PCE) of 3.8%.(Kojima, Teshima, Shirai, & Miyasaka, 2009) Researchers have found that perovskite photoactive layers exhibit promising photovoltaic properties such as tunable band gaps, high absorption coefficients, high charge carrier mobility and long charge diffusion lengths. Recent perovskite devices can produce energy conversion efficiencies comparable to those of silicon solar cells.(Jiang et al., 2022; Zhao et al., 2022) Meanwhile, due to their large absorption coefficients and color tunability, perovskite materials hold great promise for use in energy-efficient smart windows and other building-integrated technologies .(Batmunkh, Zhong, & Zhao, 2020) One of the most widely researched is the semitransparent perovskite solar cell (ST-PSCs), which can be applied directly to building facades, windows and glass roofs for solar energy harvesting.(Bing et al., 2022; Eggers et al., 2022) Colored PSC is another attractive BIPVs that has shown good suitability for building walls, fences and car park roofs.

(Y. Wang et al., 2021) A more challenging BIPV combines solar energy harvesting functions with electrochromic layers to form electrochromic functional photovoltaics. The same can be combined with thermochromic to produce thermochromic solar cells.(Ling, Wu, Su, Tian, & Liu, 2021; S. Liu et al., 2022) The main purpose of these dual-function BIPVs is to prepare smart windows that assist in cooling the building through photovoltaic conversion.

As thin film photovoltaic technology is made transparent by reducing the thickness of the active layer, it can be applied to all types of semiconductor materials without restriction. Previous research into thin film TPVs has focused on achieving high PCE using a variety of materials. However, the commercialization of TPVs also requires consideration of long-term stability and appropriate aesthetics of the device. Although organic and chalcogenide TPVs exhibit relatively high PCE, these materials lead to poor stability even in opaque photovoltaics as they exhibit inherent instability to water and oxygen.(Cha & Wu, 2021; Nazir et al.)

4. Selective light transmission technology

Another method for the preparation of high-performance TPVs is the selective light transmission technique. This method achieves light transmission in the visible region through selective light transmission regions. As early as 2014, Henry J. Snaith et al. formed ST-PSCs with neutral color and relatively high efficiency by using morphology control of perovskite films. By controlling the pores of the perovskite film, the island of perovskite film was thick enough to absorb all visible light, while the pore regions were transparent. The overall optical appearance of this film is neutral in color, resulting in the preparation of neutral ST-PSCs (Eperon, Burlakov, Goriely, & Snaith, 2014); Using this method, Henry J. Snaith et al. also prepared neutral-colored ST-PSCs with a PCE of 6.1% and an AVT of 38% through a systematic study over a two-year period.(Hörantner et al., 2016) Recently Sang Hyuk Im et al. fabricated effective neutral ST-PSCs by controlling the aperture ratio using laser patterning. The AVT was controlled by increasing the aperture ratio and finely tuning the neutral coloring. Successfully prepared 2.00 cm^2 perovskite devices with a high efficiency PCE of 12.83% and 36.00 cm^2 devices with a PCE of 9.30%, while achieving an AVT of 21.74%.(H. J. Lee et al., 2022) Similar technical approaches have been used to achieve uniformly transmissive transparent photovoltaic devices in already commercialized monocrystalline silicon solar cells. Kwanyong Seo et al. developed neutrally transparent crystalline silicon substrates and demonstrated their application for TPVs. The transparent crystalline silicon substrates were fabricated by placing micro-aperture shaped light transmitting windows onto bare crystalline silicon wafers. The transparent crystalline silicon substrate shows a completely neutral color without transmission cut-off wavelengths and its transmittance can be easily adjusted by controlling the filling section. In addition, the 1 cm^2 neutral-colored TPVs fabricated using this transparent crystalline silicon substrate show a maximum efficiency of 12.2%.(K. Lee et al., 2020) Further, Kwanyong Seo et al. used a simple and effective chemical surface treatment method for removing surface damage from crystalline silicon micropores. TPVs with a large area of 25 cm^2 with chemical surface treatment showed a transmittance of 20% PCE of 14.5% by removing the damaged surface of crystalline silicon micropores. (Park, Lee, & Seo, 2022)

The above collations reveal the use of micro-nano structures to control the pore size ratio of the micro-nano pores of the active layer films to achieve uniform and high transmission across the full spectrum. There are obvious advantages to this technology, which can be prepared by laser and wet chemical methods with a simple process. But the disadvantages are also obvious, such TPVs devices have full spectral transmission, the spectrum is not selective, and the TPVs device performance cannot reach the ideal value. As the c-Si TPVs are manufactured using the same structure as the commercial c-Si PVs, they have a similar high stability. Therefore, a rapid commercialization of c-Si TPVs is expected to be possible.

5. Luminescent solar concentrator technology

The Luminescent Solar Concentrator (LSC) is a novel photovoltaic technology with simple construction, angle independence, high defect tolerance and design flexibility.(Yang, Barr, & Lunt, 2022) LSC-type TPV technology uses luminescent materials that absorb and emit light in the UV/near IR region. The emitted light from the light emitting material is directed to the edges of the transparent polymer substrate. c-Si, GaAs and InGaP PVs are mainly used as edge PVs. Since the edge region is negligible, LSC-type TPVs have the advantage of being able to achieve perfect transparency with almost no absorption of visible light. Recent literature has reported very high AVTs of over 74% for LSC-type TPVs.(Yang et al., 2020) The size of the LSC is determined by the area of the transparent polymer substrate that includes the light emitting material. Transparent polymer substrates with light emitting material can be manufactured on a large scale using inexpensive methods such as casting, coating and roll-to-roll processes. In addition, solar cells mounted on the edges of LSCs are already commercially available on a large scale. LSC-type TPVs are therefore advantageous for building-integrated photovoltaic or vehicle-integrated photovoltaic applications that replace large-scale glass substrates. The reported efficiency of LSC-type TPVs technology is much lower than the theoretical efficiency, as current technology is far from ideal conditions. The lifetime of LSC-type TPVs depends mainly on the stability of the light-emitting material.(Yang & Lunt, 2017) This is because the other components of the LSC type TPVs, the clear polymer and the edge mounted PVs have a long life span of several years or more. Examination of the variation in absorbance of the dye embedded in the transparent polymer substrate shows that very few materials are relatively stable over a two-year period, attributed to the fact that most luminescent materials are sensitive to oxygen and moisture under atmospheric conditions, resulting in a short lifetime.

Table 1 High performance TPVs with different types

The types of TPVs	**PCE (%)**	**AVT (%)**	**LUE (%)**	**CRI**
c-Si (Park et al., 2022)	14.5	20	2.9	100
Perovskite (J. Lee et al., 2021)	12.7	25.2	3.21	-
Organic (X. Liu et al., 2022)	11.43	46.79	5.35	85.39
LSC (Huang et al., 2022)	1.57	84	1.3	88

6. Conclusion

Although TPVs have been extensively studied as a renewable energy source in urban areas, high performance TPVs have not yet achieved commercial use. When windows in buildings with a window-to-wall ratio of 55% are replaced with 30 W TPVs (AVT of 15%), more than 40% of the energy consumed in the building can be generated from PV, TPVs can be applied to vehicles in addition to this. To the end, this paper presents several key elements as important considerations for TPVs development, including (1) high PCE at the same AVT, (2) glass-like neutral color and low haze ratio, (3) modular preparation, and (4) high stability. The best candidate to meet these requirements commercially among the TPVs already developed is c-Si TPV. c-Si TPVs has a PCE of up to 14.5% (20% for AVT, Table 1), the highest among neutral colored TPVs. In addition, the stability is expected to be the same as for commercial c-Si PV. Therefore, the development of higher performance photoactive materials and roll-to-roll compatible interlayer materials and electrodes are required for several other new transparent PVs technologies. Also intensified research efforts on device lifetime, color combinations, module design and efficiency will help to make a significant impact on the transition of new PV from a new technology to a mature industry status.

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