A REVIEW ON SEMI TRANSPARENT SOLAR PANELS APPLICATION ON GREENHOUSE ROOFTOPS

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Abstract
This paper provides an overview of recent progress reached in semi transparent photovoltaic systems (STPV), which are being assessed as a potential solution to enhance the productivity of plant grown in greenhouses. Utilizing this kind of renewable energy resources, relating with plant growing is attractive solution to increase sustainability for citizens. The aim of this study is to find out recent advances for application of various semi transparent photovoltaic systems which can be integrated in greenhouses. Solar PVs are among dependable, mature and cost-effective renewable energy systems and solutions, which are promising for building integrated photovoltaics (BIPV) application. The main emerging photovoltaic candidates for BIPV are amorphous silicon, kesterite, chalcopyrite, CdTe, dye-sensitized, organic and perovskite based systems. A monographic study approach has been utilized in this investigation, in ordain to compile and analyse the photovoltaic systems for BIPV mainly investigating and comparing two main parameters: average visible transmittance (AVT) and power conversion efficiency (PCE). The rapid development of new materials and structures for the manufacture of semi transparent solar panels allows a balance to be struck between AVT, PCE and a comparison of the reviewed materials indicates that organic and perovskite are the most promising for semi-transparent solar panel production and application in greenhouse constructions, based on their PCE and AVT results.
Key words: solar cell, building integrated photovoltaics, average visible transmittance, power conversion efficiency, semi transparent.

Introduction

An attractive way to make efficient use of agricultural land and provide additional energy for crop production is to integrate photovoltaics into modern agriculture (Zhao *et al*., 2021). Greenhouses are commonly constructed in open areas with high sunlight coverage, as sunlight is essential for plant photosynthesis. For this reason, such sites are always appropriate to produce PV (photovoltaic) power (Yano & Cossu, 2019).

The structure of a greenhouse is usually made of plastic, glass or fibreglass. This allows sunlight to enter the greenhouse and photosynthesize the plants. However, a key aspect is the use of electricity to power the greenhouse, i.e., the cooling, ventilation and irrigation systems in various climatic situations. Therefore, it is preferable to use a PV system to meet the power needs in greenhouses and provide a comfortable environment in the greenhouse, rather than consuming fossil fuels and exterior energy supplies to sustain this system (Lu *et al*., 2022).

Solar PV is one of the dependable, mature and cost-effective renewable energy systems and solutions. The International Renewable Energy Agency (IRENA) has forecast the worldwide installed capacity of PV by 2050 and found that PV could potentially contribute 4.9 gigatonnes (Gt) of emission (CO_2) reductions in 2050. In Europe, installed PV power is expected to increase significantly to around 891 gigawatts (GW) by 2050 (International Renewable Energy Agency, 2019). The use of PV is also in line with opportunities for an urban energy transition in the city, as shown by a study on emission targets in the city of Riga. The transition to renewable energy sources will necessitate substantial material modifications at the household level, including the installation of PV or smart meters. Therefore, it is essential to comprehend individual and alliance values to prioritize low-carbon alternatives by citizens. This is a crucial aspect of urban energy strategies (Oliveira *et al*., 2022).

The aim of this study is to find out recent advances for application of various semi transparent photovoltaic systems which can be integrated in greenhouses. To achieve the aim in the study, a monographic study approach was used in order to compile and analyse the photovoltaic systems for BIPV mainly investigating and comparing two main parameters: average visible transmittance (AVT) and power conversion efficiency (PCE).

Materials and Methods

The research employed a monographic study approach to compile and analyse photovoltaic systems for BIVP mainly investigating and comparing two main parameters: average visible transmittance and power conversion efficiency. This study summarises scientific literature from different publications and authors. Only articles from scientific journals extradited from 2004 were utilized, while more recent papers were preferred. To select and analyse 38 full text research articles and monographs Scopus, Web of Science, MDPI Science Direct and Google scholar research databases were used. The following keywords were used in the selection of scientific literature: amorphous silicon, kesterite, chalcopyrite, CdTe, dye-sensitized, organic and perovskite, semi transparent. For this review, multiple articles were analysed, and those that conducted research in a similar manner were selected.

Results and Discussion

The majority of agricultural industry is powered by non-renewable energy sources, such as fossil fuels, which are known to be greenhouse gas emitters that contribute to climate change and global warming. Growing concerns about the environmental impact of these non – renewable fuels tend to be alleviated by more sustainable resources (Bolyssov *et al*., 2019).

Solar systems for building installation can be classified as Building-Added (BA) and Building-Integrated (BI) (e.g. facade-integrated systems, roof-integrated systems, etc.) (Lamnatou & Chemisana, 2017). The literature on greenhouse construction indicates a recent increase in interest in rooftop/BI greenhouses over the past five years. This includes rooftop/BI greenhouses with semi transparent PV cells that allow a certain percentage of solar radiation to pass through (Moreno *et al*., 2023).

The co-cultivation of crops and photovoltaic energy production on the same space is referred to as 'agrivoltaics'. The term 'agri' pertains to the science and technology of crop cultivation, while 'voltaic' refers to photovoltaic energy (Gorjian *et al*., 2022). In addition, rooftop greenhouses have the potential to create new agricultural areas in urban areas, using rooftops that would otherwise be unproductive. To optimise the energy needs of the buildings and greenhouses, this solution uses a building energy management system (Choi *et al*., 2018).

While crystalline silicon (c-Si)-based units dominate the building integrated PV (BIPV) market, the opaque characteristics of silicon compose a significant potential for the introduction of new PV technologies that can achieve true semi transparency. These include: amorphous silicon, kesterite, chalcopyrite, CdTe, dye-sensitized, organic and perovskite based systems 'Figure 1'.

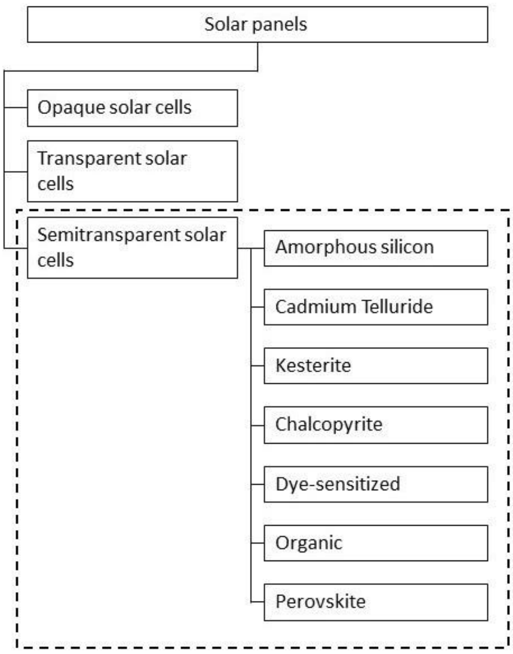

Figure 1. Classification of semi transparent solar cells for BIPV (Sun & Jasieniak, 2017).

Transparency is a crucial factor for BIPV applications. To reflect the sensitivity of the eye to different wavelengths, a parameter named average visible transmittance (AVT) has been implemented. It is computed as the average spectral transmission of visible light weighted by the photopic response of the human eye (1):

$$AVT = \frac{\int T(\lambda)P(\lambda)S(\lambda)d(\lambda)}{\int P(\lambda)S(\lambda)d(\lambda)} \quad (1)$$

In the calculation (Eq.1) of the AVT uses the ratio of the transmission (*T(λ)*), the solar photon flux (*S(λ)*), and the photopic response (*P(λ)*) (de Bruin & van Sark, 2022).

The power conversion efficiency (PCE) is another important manufacturing parameter. As shown in Equation 2, the PCE is the proportion among the electrical power produced by the side-mounted PV cell and the incident power:

$$PCE = \frac{P_{out}}{P_{in}} = \left|\frac{J_{mpp}V_{mpp}}{P_{AM1.5G}}\right| \quad (2)$$

where J_{mpp} – the current density at the maximum power point (MPP) of the cell;
V_{mpp} – the voltage at the MPP;
$P_{AM1.5G}$ – the power of the incident AM1.5G spectrum (1000 $W \cdot m^{-2}$ under standard test conditions (STC)) (de Bruin & van Sark, 2022).

Amorphous silicon

Amorphous silicon PV cells have an absorption coefficient that is one level higher than that of c-Si. Therefore, it is possible to reduce the thickness to the sub-micrometer range. For comparison, silicon solar cells typically have thicknesses in the range of hundred micrometers. This allows for tuning the required transparency. Hydrogen passivation is a critical step (in a-Si:H, where H stands for hydrogenation). The amount of hydrogen can also control the band gap. The higher band gap of 1.9-2.0 eV leads to higher visible transparency at the expense of lower short-circuit currents (Kumar *et al*., 2023).

The use of germanium in the formation of amorphous silicon-germanium (a-Si0.8Ge0.2:H) has been investigated in a recent report (Lim *et al*., 2013).

Such devices were conventionally grown from germane (GeH_4) and silane (SiH_4) in a partly hydrogenated conditions at 250 °C on a gallium-doped ZnO (ZnO:Ga) TCO. The p-i-n structure was used to fabricate the cells with ZnO: Ga serving as the top electrode. The appliance was fabricated with an active layer thickness of 150 nm to achieve transparency and demonstrated a PCE of 5.9% at an AVT of 17.9%. The comparison appliance lacking Ge achieved a PCE of 5.5% while maintaining a high level of visible transparency at 21.6% (Sun & Jasieniak, 2017).

Cadmium Telluride

A well-studied material is cadmium telluride (CdTe). It is II-VI semiconductor material with an outright band gap of 1.5 eV for single crystal and 1.42 eV for polycrystalline form. CdTe has high performance optical and electrical characteristics (Table 1). Thin-film modules, such as CdTe, have received considerable attention from the photovoltaic research community over the last two decades, consisting of thin liner cells only a few micrometers thick. Small CdTe solar cells have improved dramatically in efficiency in recent years, from 16.5% to 22.1% (Wang *et al.*, 2018) and the general module productiveness for semi transparent PV windows are estimated to be in the diapason of only 4.1%–12% (Sun *et al.*, 2018). Additionally, in the wavelength range of 500 nm to 800 nm the average transmittance can be reached 14.21% (Xie *et al.*, 2024).

Table 1

Properties of CdTe

Semiconductor	CdTe
Crystal structure	Cubic
Band gap	1.42 eV
Lattice constant	6.482 Å
Electron affinity	4.28 eV
Absorption coefficient	104 cm^{-1}
Refractive index	2.76
Density	5.85 $g \cdot cm^{-3}$
Melting point	1092 °C
Boiling point	1130 °C
Young’s modulus	3.7×10^{11} $dyne \cdot cm^{-2}$
Work function	5.7 eV
Hole mobility	65 $cm^2 \cdot Vsv^{-1}$
Electron mobility	700 $cm^2 \cdot Vs^{-1}$

Source: Kapadnis et al., 2020.

Kesterite

A structural relative of chalcopyrite, kesterite $Cu_2ZnSn(S,Se)_2$ (CZTSSe) and Cu_2ZnSnS_2 (CZTS) have lately become viable competitors to $Cu(In,Ga)Se_2$ (CIGS) absorbers due to their inexpensiveness, abundance on Earth and equally promising optoelectronic characteristics (Sun & Jasieniak, 2017).

Presently, the highest PCE for opaque CZTS appliance is 10.0%, with a short-circuit current density (J_{sc}) 21.74 mA cm^{-2}, open-circuit voltage (V_{oc}) 0.7306 V including fill factor (FF) of 69.3%, and for CZTSSe PCE is 13.6%, with a J_{sc}=36.18 mA cm^{-2}, V_{oc}=0.5375 V and FF of 69.8% (Green *et al.*, 2022). Due to their related lattice and energy transition structure to CIGS, kesterite-based technologies offer the benefits of an elevated coefficient of absorption (above 10^4 cm^{-1}), a variable band gap energy ranging from an intrinsic of 1.0 to 1.5 eV, intrinsic p-type conductibility in a range appropriate for solar cells, and three-dimensional equality of carrier transport (He *et al.*, 2021).

While various technological applications are being investigated, there is currently no existing standard for kesterite technology although a standard exists for CIGS, which is the most similar material to kesterite. Furthermore, kesterite solar cells have been researched for many years, but only a few number of papers have presented stability values for this type of cell. (Larramona *et al.*, 2020). The researchers found that there was little or no initial loss of efficiency under continuous indoor irradiation and in outdoor field tests (Larramona *et al.*, 2020).

Chalcopyrite

A co-evaporation process was used in a single stage to produce semi-transparent thin-film solar cells with an ultra-thin Cu (In, Ga) Se_2 (CIGS) absorber layers were deposited on glass substrates coated with fluorine-doped tin oxide (Larramona *et al.*, 2020). $Cu(In, Ga)Se_2$ (CIGS) based devices have gained significant interest for thin film photovoltaic utilizing owing to their high absorption coefficient, tunable band gap, compositional tolerance, excellent stability and high efficiency (Kim & Shafarman, 2016). This is due to their tunable band gap of around 1.0-1.12 eV and high absorption coefficient of up to 105 cm (Mufti *et al.*, 2020).

Quantitative performance characteristics with different CIGS absorber thicknesses illuminated from both the front side and backside at a light luminance of 100 mW cm^{-2} shown in Table 2.

Table 2

Characteristics of semi transparent solar cells with various CIGS absorber thicknesses

Absorber thickness, nm	Illumination direction	PCE, %	AVT, %
200	Front	6.89	18.53
200	Rear	4.91	-
300	Front	8.37	10.92
300	Rear	6.25	-
400	Front	9.75	5.06
400	Rear	6.46	-
2000	Front	14.89	0
2000	Rear	3.29	-

Source: Shin et al., 2021.

Dye-sensitized

Transparent solar cells, such as DSSCs, have received significant focus due to the flexibility offered by optical transparency and colour. Its inherent qualities, such as excellent low light performance and minimal angle dependence, make it suitable for BIPV (Chung *et al.*, 2020). While the manufacturing of DSSCs has been simplified, there has been an improvement in their PCE from 7% to 14%. DSSCs offer consistent performance in a variety of lighting conditions, including fluorescent and LED, strengthening their position in a variety of electronics applications, including wireless sensor networks, smart buildings, smart homes and wearable devices (Prajapat *et al.*, 2023).

Among TPV (transparent photovoltaic) technologies, DSSC technology has one of the greatest transmittance amount of solar radiation (Pulli *et al.*, 2020). Utilizing conventional red and orange dyes, the devices have been shown to achieve a solar transmittance of 20-30%, although using a chosen dye system that takes up light in the ultraviolet and near-infrared range, an astonishing transmission rate of 60% has been demonstrated (Barichello *et al.*, 2021). In recent solar cell efficiency tables, it can be found that PCE reaches 8.8-12.25% (Green *et al.*, 2022).

Organic

Fine organic particles or conductive organic polymers form the basis of organic solar cells (OSCs). Contingent on the power band gap of the light-absorbing element in the active layer, they can harness either higher-energy ultraviolet (UV) radiation or lower-energy infrared radiation and transform to electrical energy (Jain *et al*., 2024). OSCs offer great advantages in terms of lightness, ease of manufacture, low cost and environmental friendliness compared to traditional silicon-based solar cells. Recently, PCE has increased from less than 3% to over 18% (Hu *et al*., 2020).

In general, semi transparent organic solar cells (STOSCs) can be composed of a semi transparent active layer with a structure of transparent electrodes at the top and bottom, and show great potency in building windows, car windows and greenhouse roofs to meet human or plant needs (Han *et al*., 2021). Although semi transparent organic photovoltaics (STOPV) are not yet commercially available. The challenge of balancing device efficiency and AVT remains a topic of interest for researchers. Efforts are being made to increase efficiency to meet commercial standards while also optimizing AVT (Amin *et al*., 2023). The development of wide area STOSC requires increased transparency and a simple manufacturing operation as key industrial requirements. One solution is the fully solution processed IEICO-4F non-fullerene acceptor based STOSC with slot die coating, demonstrating 11% efficiency and 58% AVT (Ghosh *et al*., 2023).

Perovskite

Perovskite cells (PSCs) are of interest to researchers around the world because of their high energy conversion efficiency, inexpensive materials and ease of manufacture (Srivishnu *et al*., 2023). PSCs have excellent potential for large-scale industrialization in the near future due to the rapid growth of PCE from 3.8% to 25.5% and its low production costs (Chen *et al.*, 2022).

Perovskites are materials with an ABX3 crystal structure, and on this hybrid crystal structure, PCSs possess tunable bandgaps (1.3 - 2.2^{o}eV), high absor-ption coefficient (5.7·10^{40}cm^{-1} at 600^{o}nm), and a high degree of transparency (Noman *et al*., 2024). Compared to a solar cell design, FAPb-I3 perovskite PV cell with the highest efficiency of 25.8% and power conversion efficiency of 0% has been applied in this PV cell, and FAPb-I3 perovskite PV cell has achieved efficiency of 15.1% and power conversion efficiency of 40%. Upon full dimensional parameter improving, the AVT can attain to 41.1%, 52.6%, 33.4% and 60.3% while the efficiency of FAPbI3 perovskite PV cell is 10%, 12%, 15% and 17%, appropriately (Zhou *et al*., 2023). In recent solar cell efficiency tables, it can be found that PCE reaches 17.9 – 29.8% (Green *et al*., 2022).

PSC has excellent commercial potential, but there are so many factors that need to be addressed. The efficiency of PSCs can be affected by several factors, including the prohibitive cost of gold electrodes, additives, temperature, moisture and UV illumination, degradation in the presence of oxygen, toxicity of lead, thermal stress, electrical bias, and interface. It is important to consider these factors when evaluating the result of PSCs (Sharma *et al*., 2022).

In the case of the solar cells discussed in this article, it is evident that the majority of the evolving semi transparent categories now are at a commercial level, but from an aesthetic point of view, the colour and component construction need to be seriously rethought. Due to the non-unchanging absorption coefficient of absorbing films and the multi-layered nature of PV cells, the irradiance passing through the cells modify the spectral colours coordinates of the passing sunlight to a varying degree depending on the density of the absorber layer (Sun & Jasieniak, 2017).

Conclusions

1. Comparing the reviewed materials, shows that the most promising materials for semi transparent solar panel production and application in greenhouse constructions could be organic and perovskite, due to the results achieved by their PCE and AVT.
2. With the rapid development of new materials and structures for the manufacture of semi transparent solar panels, it is possible to achieve a balance between average visible transmittance (AVT), power conversion efficiency (PCE), and design of construction, which allows to vary temperature, the intensity of the required light and the colour spectrum according to the goal to be achieved, in the same time fulfilling certain requirements of power needs.

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