

Design and Characterization of Semi-Transparent Silicon-Based Photovoltaic Modules for Dual-Use Solar Applications

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Abstract: The integration of semi-transparent photovoltaic (STPV) panels into agricultural and greenhouse systems offers a promising pathway for achieving dual land use - simultaneous crop cultivation and solar power generation. This study presents a comprehensive theoretical and experimental analysis of two monocrystalline silicon-based STPV panel configurations designed for optimal light transmission and energy output under the climatic conditions of Jizzakh Region, Uzbekistan. The panels were fabricated using tempered glass–EVA–glass structures with controlled inter-cell spacing, resulting in light transmittance levels of approximately 54% (Type 1) and 68% (Type 2) in the visible spectrum. Spectrophotometric measurements confirmed that transmittance within the 400–700 nm photosynthetically active radiation (PAR) range reached 85–95%, ensuring sufficient illumination for crop photosynthesis. A solar radiation transmission model was applied for tilt angles between 25° and 45°, revealing that a 35° inclination provides optimal annual irradiance balance. Comparative analysis with crop-specific daily light integral (DLI) requirements demonstrated that Type 2 panels are suitable for high-light-demand crops (e.g., tomato, cucumber, eggplant, bell pepper), while Type 1 panels are more appropriate for moderate-light vegetables (e.g., lettuce, basil). The findings support the use of customized STPV panel designs in agrivoltaic applications to improve both energy efficiency and plant productivity, contributing to sustainable agricultural development in arid and semi-arid regions.

1 INTRODUCTION

Since solar energy has a lower energy density than fossil fuels, particularly wide installation areas are necessary to increase photovoltaics' (PVs') power output. Due to environmental policies like the Paris Agreement, the deployment of PV systems has grown rapidly in recent years. There may be competition for such property in the future for PVs and other applications that require sunlight, though, as the lack of installation sites in urban and suburban regions becomes a problem. One viable way to address this issue is through dual land use. Particularly, agrophotovoltaics, photovoltaic agriculture, or solar sharing the practice of using land for both PVs and agriculture is a phenomena that is rapidly developing globally [1]–[4]. In this instance, the PV modules are

situated on farmland, allowing for the simultaneous production of electricity and farming. However, the intended power yield needs to be produced without compromising the energy yield or quality of the plants and crops. There is a trade-off between power generation and sunlight transmission in the case of PV modules.

For example, Si solar cells found in most commercial PV modules are totally opaque to sunlight. Stated differently, the amount of sunlight that reaches the ground through a photovoltaic module reduces according to the area where the module is installed [5], [6]. To enhance module transparency, two main approaches have been explored: partially transparent PV modules that use opaque solar cells with clear spacing between them, and modules manufactured from semitransparent

solar cells. Both approaches, however, still face similar trade-off challenges between light transmission and power generation. To overcome this limitation, further design innovations are necessary, and numerous studies have attempted to develop advanced PV modules that achieve a better balance between these competing requirements [7]–[9].

For instance, there have been reports of a partially transparent photovoltaic module with a light-tuning fluorescent layer that turns the green portion of the incident sunlight into red light. [10]. Since the red light spectrum is the most sensitive for both photosynthesis by plants and power generation by Si cells, it is especially effective for both farming and power generation. A concentrator photovoltaic (CPV) module using a parabolic concentrator with a multilayer dichroitic film was proposed by Zhang et al. [11], who concentrated on the wavelength-splitting technology. In addition to focusing the remaining sunlight onto Si cells for power generation, the parabolic concentrator selectively transmits sunlight only in a particular spectral range that is necessary for plant growth to the area beneath the module. Using highly transparent high-concentration CPVs that selectively transmit diffuse sunlight is another strategy that researchers have suggested [12].

A 57 mm × 57 mm minimodule was designed and constructed, and tests were conducted outdoors. The outcomes validated the concept's viability. In this work, we designed and built two kinds of practically sized, extremely transparent CPV modules and tested them outdoors to further validate the concept's viability. We contrasted the results with those of a conventional PV module that was believed to be partly transparent [13].

2 MATERIALS AND METHODS

2.1 Research Site and Climatic Conditions

The research was conducted during 2024–2025 at the Scientific-Practical Center for Renewable Energy Research under the Jizzakh Polytechnic Institute. The site is located in a region with a continental climate, where summer temperatures can rise up to +40°C, while winter temperatures may drop to −5°C. The geographical coordinates of the research area are: latitude 39.789°N, longitude 67.50°E, and altitude 380 meters above sea level.

2.2 Device Fabrication

We first examine the general production features of the two solar panel types. These semi-transparent solar panels are constructed using a high light-transmittance layer of EVA (ethylene-vinyl acetate), with dimensions of 2273×1125×0.5 mm and a unit weight of 380 g/m². This EVA layer is placed onto a tempered glass sheet measuring 2273×1128×3.2 mm.

On top of the EVA, A-grade monocrystalline solar cells are mounted. These cells have an electrical conversion efficiency of 23.2%. Another layer of EVA (380 g/m²), also featuring high light transmittance, is applied over the solar cells, followed by a second sheet of tempered glass.

All layers are laminated using a specialized laminating machine at a temperature of 142°C and a pressure of 0.8 MPa.

The two panel types differ in the layout of their solar cells, as illustrated in Figure 1, with the key differences summarized in Table 1. Before cell placement, each solar cell of 90 mm × 182 mm is cut into two equal parts.

In the first panel type, the segmented cells are spaced 49 mm apart and connected in series groups of 12 cells using wires measuring 0.18 × 0.5 mm. Twelve such 12-cell strings (12S) are interconnected in parallel with 0.35 × 4 mm bus wires, resulting in a total of 144 cells per panel Figure 1a.

In the second panel type, the cells are spaced 62.66 mm apart and connected in series groups of 10 cells using 0.18 × 0.5 mm wires. Twelve such 10-cell strings (10S) are interconnected in parallel with 0.35 × 4 mm bus wires, resulting in a total of 120 cells per panel Figure 1b.

2.3 Optical Properties of Semi-Transparent Photovoltaic Panel

Chen and co-researchers simulated the performance of glass, EVA, PV cells and confirmed there were considerable variations in light transmissivity, absorbance, and reflectance, depending on the thickness of the material [15], density, and thermal conductivity as shown in Table 2. As part of this study, the spectral light transmittance of the open (non-cell) region of the semi-transparent solar panel was measured using a Specord 50 spectrophotometer (Analytik Jena, Germany, 2005) located in the laboratory of the

Table 1: Presents the key differences between the two panel configurations.

Parameter	Panel Type 2	Panel Type 1
Light transmittance	68%	54%
Cell efficiency (STC)	23.2 %	23.2%
Number of solar cells	120 cells	144 cells
Cell dimensions	182 mm × 45 mm	182 mm × 45 mm
Spacing between cells	62.66 mm (Figure 1b)	49 mm (Figure 1a)
Glass dimensions	2273 mm × 1128 mm × 3.2 mm	2273 mm × 1128 mm × 3.2 mm
EVA density and certification	380 g/m ² , TÜV certified	380 g/m ² , TÜV certified

Optics Department at Samarkand State University (SamSU). The device operates accurately within the 190–1100 nm range in the UV–VIS–NIR spectrum, enabling a comprehensive assessment of the optical properties. Detailed results are presented in Figure 2.

transmittance reaches near-maximal levels: 85.92% at 400 nm, 91.11% at 500 nm, 94.24% at 600 nm, and 95.51% at 700 nm. This high transmission in the PAR range confirms that the panel can provide sufficient light intensity for healthy plant growth beneath it.

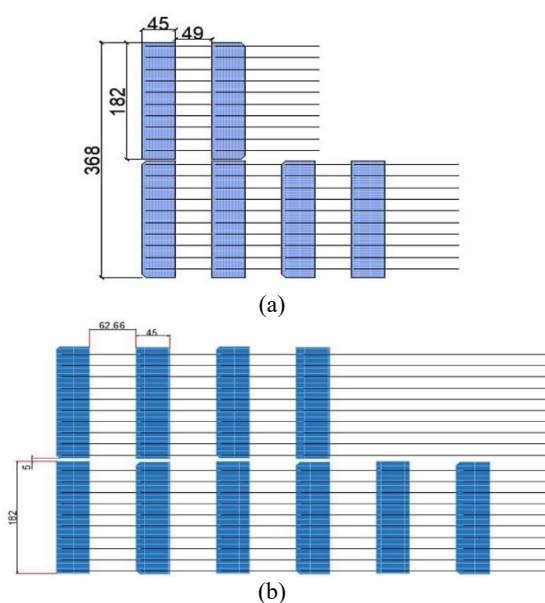


Figure 1: a) Layout of solar cells in the first type of semi-transparent solar panel; b) Layout of solar cells in the second type of semi-transparent solar panel.

The measurement results revealed that in the 200–300 nm range, the light transmittance values were extremely low - for instance, 0.08% at 200 nm and 0.106% at 250 nm - indicating that the panel material almost completely absorbs UV-B and UV-C wavelengths. This characteristic plays a critical role in protecting plants beneath the panel from harmful high-energy radiation.

From 300 nm onward, light transmittance increases rapidly: reaching 19.69% at 310 nm and 41.72% at 320 nm, which corresponds to the beginning of the Photosynthetically Active Radiation (PAR) range. In the 400–700 nm range, the

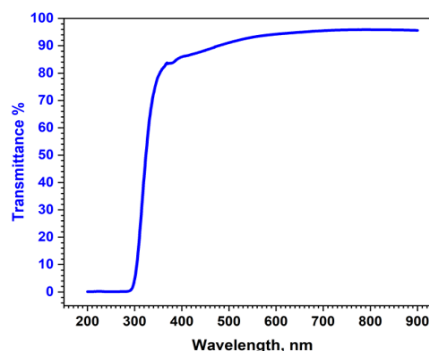


Figure 2: Wavelength-dependent light transmittance of the transparent part of a semi-transparent solar panel.

In particular, the 430–670 nm range (corresponding to blue and red wavelengths), where chlorophyll absorbs light most actively, exhibits high transmittance, which facilitates efficient photosynthesis.

In the 700–900 nm range (i.e., the near-infrared region), the light transmittance also remains high, reaching up to 95.6%. This contributes to thermal energy transfer and supports the overall energy balance within the greenhouse.

The transparent material of the solar panel exhibits strong absorption in the UV range below 300 nm, effectively blocking the components of solar radiation that are harmful to plants. In the PAR range (400–700 nm), the transmittance is maintained between 85% and 95%, providing optimal light conditions for photosynthesis.

The high transmittance in the near-infrared (NIR) range aids in maintaining thermal equilibrium, which further supports the application of such panels as transparent greenhouse covers.

2.4 Theoretical Comparison of Solar Radiation Transmission at Different Tilt Angles

Determining the optimal tilt angle for semi-transparent photovoltaic panels integrated into greenhouses is one of the key factors for maximizing energy efficiency while ensuring sufficient light conditions for plant growth [14]. To analyze how solar radiation varies throughout the year in relation to the tilt angle, the light transmittance of Type 1 and Type 2 semi-transparent solar panels was theoretically calculated at tilt angles of 25°, 30°, 35°, 40° and 45°.

The calculations were based on the annual solar radiation flow at a specific geographic point in Uzbekistan: Jomboy district, Samarkand region (39.789°N latitude, 67.50°E longitude, 380 m altitude), and employed the following (1). Where in (1): I_{0e} : daily annual solar energy ($\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$); I_{gs} : extraterrestrial solar radiation; δ : solar declination angle; ω_1 , ω_2 : hour angles of sunrise and sunset; β : panel tilt angle; φ : geographic latitude (39.789°N); θ : semi-transparent solar panel azimuth angle. At each tilt angle, solar radiation transmitted through the panels was calculated for each month on the 1st, 11th, and 21st day, from January through December.

In Figures 3a, 3b, 3d, 3e, and 3f, the comparative results are illustrated: solar radiation falling on a solar panel (black), passing through a Type 1 semi-transparent panel (red), incident on a horizontal surface (green), and passing through a Type 2 semi-transparent panel (blue).

At 25° tilt Figure 3a: Type 1 panels transmitted solar radiation ranging from 10,553 to 14,176 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, while Type 2 panels ranged from 13,801 to 18,538 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. The higher transmittance of Type 2 resulted in greater overall energy throughput; however, Type 1 panels filtered the spectrum more effectively for photosynthesis, thereby creating a more favorable environment for plant development.

At 30° tilt Figure 3b: Radiation through Type 1 panels ranged from 11,183 to 13,990 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, and for Type 2 panels, from 14,624 to 18,295 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. This tilt demonstrated the highest efficiency under summer conditions and is therefore recommended for use in warm seasons.

At 35° tilt Figure 3c: With the lower solar altitude in winter, this angle proved more effective for heat retention. Type 1 panels transmitted between 11,911 and 13,990 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, while Type 2 panels transmitted up to 16,782 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. This makes 35° particularly suitable for winter lighting and thermal conditions.

At 40° tilt Figure 3d: Type 1 panels transmitted 12,548 to 14,995 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, and Type 2 panels transmitted 16,409 to 18,482 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. Despite the higher transmission of Type 2, Type 1 panels maintained a better balance between light for photosynthesis and energy utilization.

At 45° tilt (Figure 3e): Radiation values for Type 1 panels ranged from 13,093 to 14,133 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, while Type 2 panels transmitted 17,122 to 18,482 $\text{Wh}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$. Although this tilt provided the highest annual radiation, excessive light intensity could potentially have adverse effects on plant growth in greenhouse environments.

2.5 Suitability of Plant Light Requirements Under Semi-Transparent Solar Panels

The theoretical analyses indicate that both types of semi-transparent solar panels (Type 1 and Type 2) transmit different amounts of photosynthetically active radiation (PAR) throughout the year. Specifically, the Type 2 panel provides an annual average daily light integral (DLI) of approximately 18.5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, which is sufficient for high light-demanding fruiting crops. In contrast, the Type 1 panel delivers about 13 $\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, making it more appropriate for vegetables with low to moderate light requirements.

The amount of energy in the Photosynthetically Active Radiation (PAR) range: 400–700 nm plays a decisive role in plant growth and productivity. Therefore, when cultivating crops under semi-transparent solar panels, it is essential to select plant species based on their Daily Light Integral (DLI) requirements. DLI refers to the total amount of light (in $\text{mol}/\text{m}^2\cdot\text{day}$) received by the plant over a 24-hour period and directly influences plant physiological responses.

According to recent studies, fruiting vegetables such as tomato, eggplant, and cucumber typically require a Daily Light Integral (DLI) in the range of 20 to 30 $\text{mol}/\text{m}^2\cdot\text{day}$ to achieve optimal growth and productivity [16] (Table 3). Bell pepper also performs best within a slightly lower DLI range of 18 to 25 $\text{mol}/\text{m}^2\cdot\text{day}$, making it moderately light-demanding. In contrast, leafy vegetables such as lettuce and basil thrive under more moderate light conditions, with ideal DLI levels of 12 to 16 $\text{mol}/\text{m}^2\cdot\text{day}$ [17], [18]. Moreover, various shade-tolerant herbs and leafy greens are capable of sustaining healthy growth with DLI levels as low as 6 to 10 $\text{mol}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$, making them suitable for lower-light greenhouse environments [20], [21].

$$I_{0e} = \frac{24}{\pi} \cdot I_{gs} \cdot f \cdot \left[\frac{\pi}{180} (\omega_2 - \omega_1) \cdot \sin\delta \cdot (\sin\varphi\cos\beta - \cos\varphi\sin\beta\cos\theta) + (\sin\omega_2 - \sin\omega_1) \cdot \cos\delta \cdot (\cos\varphi\cos\beta + \sin\varphi\sin\beta\cos\theta) - (\cos\omega_2 - \cos\omega_1) \cdot \cos\delta\sin\beta\sin\theta \right]. \quad (1)$$

Table 2: Optical properties of materials used in semi-transparent photovoltaic panels.

Materials	Light transmission	Reflectance	Absorbance
Glass	95%	4%	1%
EVA	97%	0%	3%
PV cells	0%	7%	93%

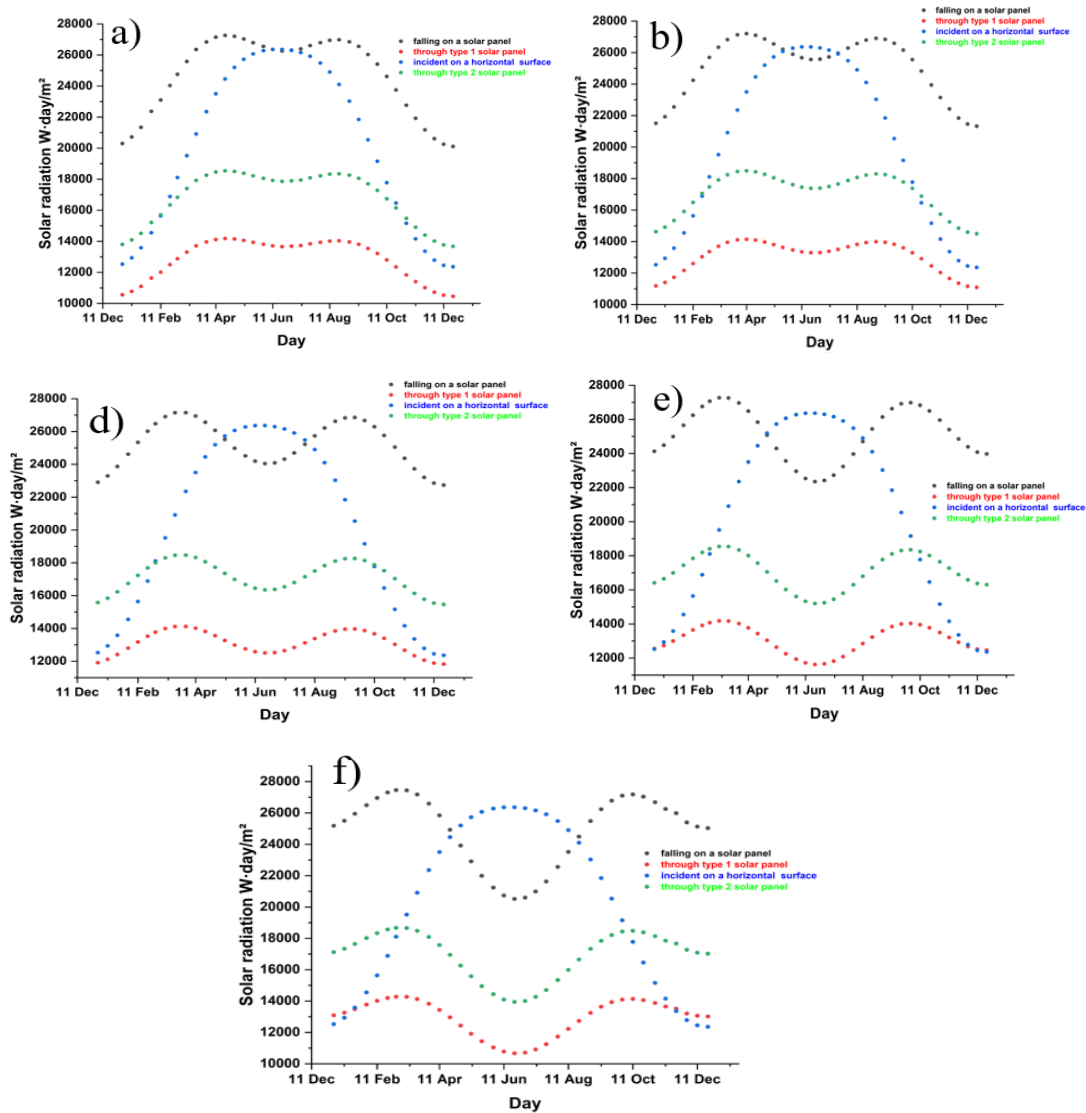


Figure 3: Annual solar radiation transmission (W/ day·m²) through Type 1 and Type Two semi-transparent PV panels were evaluated at different tilt angles: (a) 25°, (b) 30°, (c) 35°, (d) 40°, and (e) 45°.

Table 3: Compatibility of semi-transparent solar panel types with crop light requirements based on DLI thresholds.

Crop Type	DLI Requirement (mol·m ⁻² ·day ⁻¹)	Recommended Panel Type	Notes
Tomato	20–30	Type 2	High light demand; grows efficiently under Type 2
Cucumber	20–30	Type 2	Yield strongly affected by light intensity
Eggplant	20–30	Type 2	Prefers high-light environments
Bell Pepper	18–25	Type 2	Fruit quality is closely linked to sufficient light
Lettuce	12–16	Type 1	Capable of growing in relatively low-light environments
Dill, Basil, Herbs	6–12	Type 1	Shade-tolerant; grows well even under reduced light

Furthermore, due to the higher light transmittance of the Type 2 panel, its electricity generation is slightly lower. In contrast, the Type 1 panel contains a higher number of photovoltaic cells, thus producing more electricity, although it allows less light to pass through [19].

Therefore, selecting the appropriate panel type must be strategically aligned with the light requirements of the crops and the energy demands of the greenhouse.

3 CONCLUSIONS

This research looked at both the theory and experimental performance of two types of semi-transparent photovoltaic (PV) panels (Type 1 and Type 2). These panels were made with standard solar cells for use in agriculture. The study looked at five different tilt angles: 25°, 30°, 35°, 40°, and 45°. It was done in the continental climate of the Jizzakh area in Uzbekistan. Using a tested model of solar radiation transmission, it was discovered that a 35° tilt was the best way to catch solar energy all year, especially in the winter. This was because it kept the temperature stable and let enough light through.

We checked the panels' optical qualities by measuring how much light they let through in the UV, PAR, and NIR ranges. Transmittance levels hit 85–95% in the important 400–700 nm PAR range, which is needed for photosynthesis. This shows that the panels can be used in greenhouses.

Type 1 panels were more efficient at making electricity, but they let less light through, so they were better for crops that can grow in shade, like lettuce, basil, and leafy greens. Type 2 panels, on the other hand, let more light through and are better for crops

that need a lot of light, like tomatoes, eggplants, and cucumbers, even though they make a little less power.

The results also showed that the sun transmittance characteristics matched the daily light integral (DLI) needs of different crops. This shows that to make a good panel, you need to balance not only energy output but also spectral light quality and the needs of each crop. Adding semi-transparent PV panels to gardens could help Uzbekistan's sustainable agriculture, make the country less reliant on the power grid, and make it easier for people to get energy.

To make the relationship between making electricity and plant growth even stronger, more study should be done on optimized panel configurations, light-selective coatings, and dynamic tilt mechanisms.

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