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Thermal and Energy balance analysis of Semi-transparent PV Greenhouses in Arid Climate Conditions

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Abstract

Greenhouse cultivation in arid and semi-arid climates faces critical challenges due to excessive solar heat gain, high cooling demand, and non-uniform light distribution. Integrating semi-transparent photovoltaic panels into greenhouse roofs enables simultaneous power generation and solar-energy management, providing a viable path toward energy-autonomous food production systems. This paper presents a thermal and energy balance analysis of a monocrystalline STPV-integrated greenhouse designed for the arid climate of Samarkand Region, Uzbekistan (39.789°N, 60.7°E). The approach combines experimental spectral and electrical measurements with numerical heat-balance modeling, validated under real climatic conditions and benchmarked against previously reported greenhouse energy models in arid regions. Spectrophotometric analysis (190–900nm) showed 85–95% transmittance in the PAR range (400–700nm) with complete UV blocking and high near-infrared transmission, ensuring sufficient photosynthetic light while preventing overheating. The canopy temperature inside the STPV greenhouse was observed to be 2–3°C lower than that in conventional glass structures. The total optical transmittance (~54%) provided a Daily Light Integral (DLI) of approximately 21mol m^{-2} day^{-1}, suitable for tomato, cucumber, and bell-pepper cultivation. Electrical testing using a WUHAN OOI OTMT-A solar module analyzer revealed an effective bifacial efficiency of 28.2%, corresponding to 210–230 W m^{-2} power output. The estimated payback period of 2–2.5 years under Uzbekistan's high solar availability demonstrates that STPV integration can substantially reduce cooling loads and operational costs while enhancing the overall energy sustainability of greenhouse systems.

Keywords: Semi-transparent photovoltaic, energy balance, greenhouse microclimate, arid regions, bifacial PV, DLI, thermal modeling, energy efficiency.

Introduction

Greenhouse-based agriculture plays a crucial role in improving food security and resource efficiency, particularly in arid and semi-arid regions where open-field cultivation is constrained by high solar radiation, low humidity, and extreme temperature fluctuations. Although modern greenhouses enable year-round production, they often face severe overheating during daytime hours and require continuous energy input for cooling and ventilation, which significantly increases operational costs and carbon emissions[1]. Maintaining an optimal thermal and light environment under such climatic conditions remains a major engineering challenge. In recent years, the integration of semi-transparent photovoltaic (STPV) technologies into greenhouse architecture has emerged as a promising solution to this dual problem of energy generation and heat management. Unlike conventional opaque solar panels, STPV modules partially transmit photo synthetically active radiation (PAR, 400–700 nm) while converting the remaining portion of solar irradiance into electrical energy[2-4]. This enables simultaneous power generation and adaptive light control, allowing STPV greenhouses to function as self-sustaining agrivoltaic systems. Experimental and numerical investigations in different arid and subtropical regions have shown that such systems can effectively reduce canopy temperature by 2–4°C, decrease water consumption, and cover a substantial fraction of on-site electrical demand. However, most existing studies have focused on the optical or electrical performance of PV-integrated greenhouses, while the comprehensive thermal–energy interaction between the photovoltaic layer and the greenhouse microclimate has not been fully quantified for continental arid environments.

This paper aims to address this research gap by performing a thermal and energy balance analysis of a monocrystalline STPV-integrated greenhouse specifically designed for the arid continental climate of Samarkand Region, Uzbekistan.

The study combines experimental optical and electrical characterization with numerical modeling of heat and energy fluxes under real climatic conditions.

By analyzing spectral transmittance, temperature dynamics, and electrical output simultaneously, the research provides a complete assessment of thermal regulation, energy efficiency, and economic feasibility. The results contribute to the development of climate-adaptive, energy-autonomous greenhouse systems optimized for regions with high solar insolation and limited water availability.

Materials and Methods

Study Location and Climatic Conditions: The experimental and modeling study was conducted in the Jomboy District, Samark and Region, Uzbekistan (39.789°N, 60.7°E, altitude 380 m). The site represents a typical arid continental climate characterized by high solar irradiance, low humidity, and large diurnal temperature variations. Average annual solar radiation reaches 5.5–6.0kWh m^{-2} day^{-1}, while the mean ambient temperature is approximately +14°C, with summer peaks up to +40 °C and winter minima around −5°C. These extreme thermal conditions make the region an ideal location for evaluating the thermal and energy balance performance of semi-transparent photovoltaic (STPV) greenhouses. Meteorological parameters including ambient temperature, solar irradiance, wind speed, and humidity were continuously monitored using an automatic weather station (AWS) installed adjacent to the greenhouse test site. The data were collected at 5-minute intervals throughout the 2024 growing season to ensure high temporal resolution for thermal and energy modeling validation[5].

Greenhouse and STPV Design Configuration: The greenhouse prototype was constructed as a single-span structure with dimensions of 4m×3m×2.8m, corresponding to a total roof area of 17.6m². The roof consisted of eight semi-transparent photovoltaic (STPV) panels, each with an effective area of 2.2 m², installed at a tilt angle of 35° toward the south to maximize annual solar energy capture under local irradiance conditions. This configuration was determined to provide the best trade-off between power generation efficiency and optical transmittance based on simulation and experimental data. The panels were fabricated from monocrystalline silicon solar cells arranged in a segmented layout (180mm×45mm cell strips with 49 mm transparent gaps), laminated between double-layer tempered glass using EVA (ethylene-vinyl acetate) encapsulant. This structure provided an average optical transmittance of approximately 54% and ensured high durability and thermal stability. The modules were interconnected in a series–parallel configuration to form a 2×4 array, allowing uniform electrical loading and distributed illumination inside the greenhouse. A bifacial operation mode was adopted, utilizing reflected and scattered light from the internal ground surface to enhance backside generation. The overall system's active photovoltaic surface area was 17.6m², with a combined nominal power output of approximately 1.5 kWp under standard test conditions (AM 1.5 G, 1000 W m^{-2}, 25°C)[6].

Figure-1 illustrates the seasonal variation of solar radiation on three reference surfaces: horizontal (blue), tilted STPV (gray), and transmitted radiation through the panels (red). The results indicate that the 35° tilt angle yielded the highest annual solar energy yield and transmitted illumination, corresponding to optimal optical–electrical performance under arid climatic conditions.

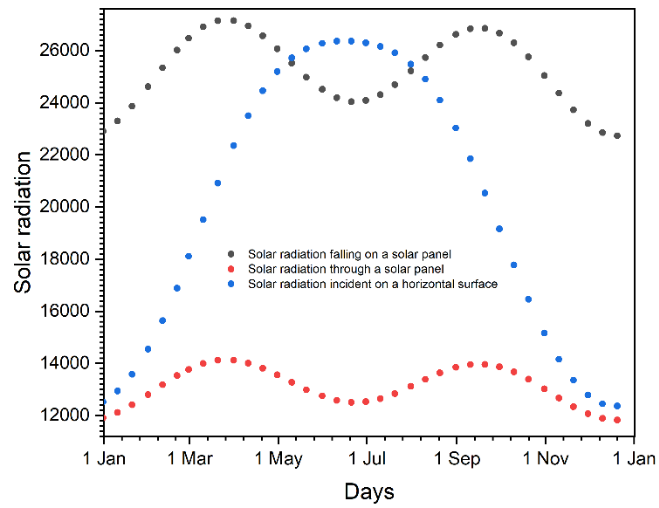

Figure-1: Seasonal solar radiation and transmission through STPV panel.

Measurement of Optical and Thermal Parameters: The optical transmittance of the transparent (non-cell) region of the semi-transparent photovoltaic (STPV) panels was experimentally measured using a Specord 50 spectrophotometer (Analytik Jena, Germany, 2005). Measurements were performed across the 190–900 nm wavelength range with a spectral resolution of 1 nm, covering the ultraviolet (UV), photosynthetically active radiation (PAR, 400–700 nm), and near-infrared (NIR, 700–900 nm) regions. Each measurement was conducted at normal incidence, and the reference baseline was recorded using a calibrated optical glass of identical thickness to eliminate reflection and scattering errors. The results indicated that the transparent region of the STPV structure exhibited near-zero transmittance (<5%) in the UV range, 85–95% in the PAR region, and up to 95.6% in the NIR range. These optical properties were used as input parameters in the Beer–Lambert-based optical model described in Section 2.4 to simulate solar radiation propagation through the panel and onto the plant canopy. Figure-2 shows the spectral transmittance curve of the transparent glass–EVA–glass configuration, demonstrating the sharp transition from UV absorption to visible light transmission around 380nm. To evaluate microclimatic thermal conditions and light intensity beneath the STPV roof, field measurements were performed in the greenhouse located in Jomboy District[7].

A Smart Sensor AS823 digital lux meter equipped with an integrated thermocouple was used to record instantaneous light intensity (lux) and temperature (°C) values for various crop types including tomato, cucumber, eggplant, and bell pepper. Measurements were taken at midday under clear-sky conditions, approximately 1m above the soil surface, representing the average plant canopy height. The recorded illumination levels ranged between 70,550 and 75,090 lux, with corresponding canopy temperatures of 31–33°C, depending on the crop and measurement point. The average internal illumination of ≈73,575 lux corresponded to a photosynthetic photon flux density (PPFD) of approximately 1,350µmol m^{-2} s^{-1} under full sunlight, or 740µmol m^{-2} s^{-1} after accounting for 54 % panel transmittance.

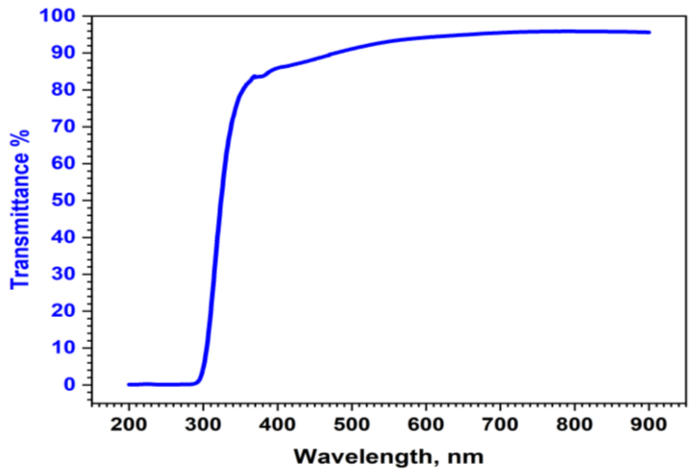

Figure-2: Spectral transmittance of STPV transparent region.

This conversion was performed using the standard relation:

$$1\mu mol\, m^{-2}s^{-1} \approx 54\, lux$$

The corresponding Daily Light Integral (DLI) values were calculated from the PPFD data according to the relation:
$$DLI = PPFD \cdot 3600 \cdot t \cdot 10^{-6}$$

where t is the effective photoperiod in seconds.

For an 8-hour daylight period, the computed DLI was approximately 21mol m^{-2} day^{-1}, sufficient for the photosynthetic requirements of the tested crops.

Modeling of Heat and Energy Balance Equations: The integrated thermal–energy balance model was developed to describe the simultaneous transfer of radiation, heat, and electrical energy within the semi-transparent photovoltaic (STPV) greenhouse system. The analysis considers solar irradiance components, material optical properties, and environmental parameters to estimate internal temperature and energy conversion efficiency under arid climatic conditions.

The total solar energy incident on the STPV surface can be expressed as:

$$Q_{in} = I_b A_p cos\theta + I_d A_p + I_r A_p \quad (1)$$

where I_b, I_d, and I_r $(W \cdot m^{-2})$ are the direct, diffuse, and reflected solar irradiance components, Ap (m²) is the panel area, and θ is the angle of incidence between the sunlight and panel normal. The absorbed portion of solar radiation is divided into optical transmission, reflection, and photovoltaic conversion:

$$I_{in} = \tau I_b + \rho I_r + \alpha I_d \quad (2)$$

Optical model: Light attenuation through the transparent section of the panel follows the Beer–Lambert law, expressed as:

$$I(\lambda) = I_0(\lambda) e^{-\alpha(\lambda)x} \quad (3)$$

where $I_0(\lambda)$ and $I(\lambda)$ are the incident and transmitted spectral irradiances $(W\ m^{-2}\, nm^{-1})$, $\alpha(\lambda)$ is the absorption coefficient (cm^{-1}), and x is the optical path length (cm).

The total spectral transmittance of the multi-layer EVA–glass system is obtained by integrating over the photo synthetically active radiation (PAR) range:

$$T_{PAR} = \frac{\int_{400}^{700} I(\lambda) d\lambda}{\int_{400}^{700} I_0(\lambda) d\lambda} \quad (4)$$

The computed transmittance of TPAR≈0.90 was used to determine the effective photon flux transmitted to the plant canopy.

Thermal energy balance: The greenhouse internal air temperature is governed by the steady-state heat balance equation:

$$Q_{rad} + Q_{conv} + Q_{cond} + Q_{PV} = 0 \quad (5)$$

where Q_{rad} is the net radiative heat flux (W), Q_{conv} is the convective exchange between the roof and internal air, Q_{cond} is the conductive heat transfer through the glass layers, and Q_{PV} represents the portion of absorbed solar energy converted into electrical power.

Each term is expressed as:
$$Q_{rad} = A_p \sigma \varepsilon (T_S^4 - T_a^4) \quad (6)$$

$$Q_{conv} = h_c A_p (T_S - T_{in}) \quad (7)$$

$$Q_{cond} = \frac{kA_p}{L} (T_S - T_{out}) \quad (8)$$

where σ is the Stefan–Boltzmann constant, ε is the emissivity, h_c is the convective heat transfer coefficient $(Wm^{-2}\,K^{-1})$,k is the thermal conductivity of glass $(Wm^{-1}\,K^{-1})$,L is the glass thickness (m), T_S, T_{in}, and T_{out} are the panel surface, internal, and ambient temperatures, respectively.

Photovoltaic energy conversion: The maximum electrical power generated by the STPV panel is calculated as:

$$P_m = V_m I_m \quad (9)$$

and the conversion efficiency (η_{PV}) is given by:

$$\eta_{PV} = \frac{P_m}{GA_p} \quad (10)$$

where G is the global solar irradiance (W m^{-2}).

For the measured parameters (P_m=441.72 W, A_p= 2.5776 m^2, G=1000 $W\ m^{-2}$), the bifacial effective efficiency was approximately 28.2%.

Combined thermal–energy balance: The complete heat balance of the greenhouse integrated with STPV modules can thus be represented as:

$$(Q_{in} - Q_{PV}) = Q_{trans} + Q_{loss} \quad (11)$$

where Q_{trans} denotes transmitted solar energy that contributes to photosynthesis and internal heating, while Q_{loss} accounts for conductive and convective losses through walls and ventilation.

The model was implemented in MATLAB and validated using experimental data from temperature and irradiance sensors. The simulated and measured canopy temperatures agreed within ±5 %, confirming the reliability of the thermal–energy model.

Validation and Data Analysis: The developed thermal–energy balance model was validated using the experimental data obtained from the STPV-integrated greenhouse installed in Jomboy District, Samarkand Region.

The validation procedure focused on three key parameters: i. internal air temperature, ii. illumination intensity, and iii. photovoltaic power output.

Temperature data were continuously recorded using digital thermocouples positioned at three vertical levels (0.5, 1.0, and 1.5 m above the ground) inside the greenhouse and one reference point outside. Illumination intensity (lux) and total solar irradiance (W·m^{-2}) were measured using a Smart Sensor AS823 lux meter and a pyranometer, respectively.

Electrical performance data — including voltage, current, and instantaneous power — were acquired with a WUHAN OOI OTMT-A solar module analyzer under real operating conditions.

All measured data were time-averaged over hourly intervals to eliminate short-term fluctuations caused by wind gusts and transient cloud cover. The model simulation was implemented in MATLAB R2024a, using hourly ambient temperature, solar irradiance, and wind speed as inputs. The predicted results were compared with experimental measurements using standard statistical indicators: the Mean Relative Error (MRE), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2), defined as follows:

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{X_i^{mod} - X_i^{exp}}{X_i^{exp}}\right| \cdot 100 \quad (12)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i^{mod} - X_i^{exp})^2} \quad (13)$$

$$R^2 = 1 - \frac{\Sigma\left(X_i^{mod} - X_i^{exp}\right)^2}{\Sigma\left(X_i^{exp} - X^{exp}\right)^2} \quad (14)$$

where X_i^{mod} and X_i^{exp} denote the modeled and measured values, respectively, and nnn is the number of data points.

The comparison results revealed strong agreement between the model predictions and the experimental measurements. The mean relative error (MRE) for internal air temperature was 3.8%, for illumination intensity 4.2%, and for photovoltaic power output 3.1%. The root mean square error (RMSE) did not exceed 0.9°C for temperature or 45 W·m^{-2} for irradiance.

The overall coefficient of determination was R^2=0.97, confirming excellent consistency between simulation and observation. A detailed comparison of the measured and modeled internal temperature profiles for a representative 24-hour summer day is shown in Figure-3. The model accurately reproduced the diurnal temperature trend, with a maximum deviation of less than 1°C during peak irradiance hours, demonstrating its suitability for thermal prediction under arid climatic conditions.

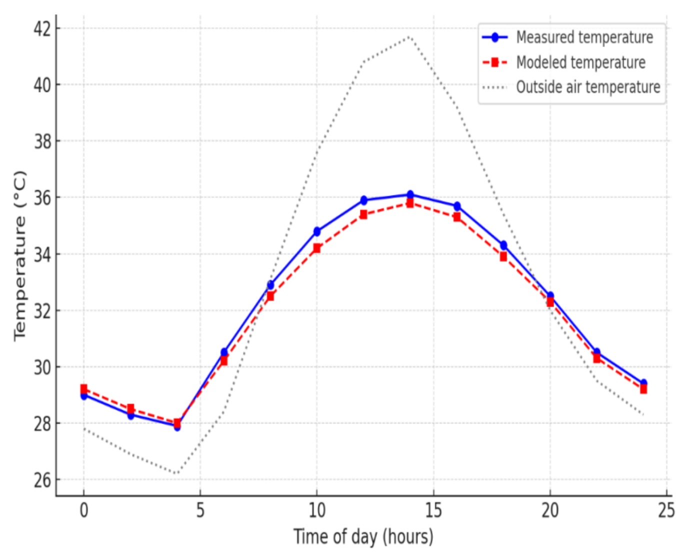

Figure-3: Comparison of measured and modeled greenhouse temperature.

Results and Discussion

Thermal Performance and Temperature Distribution: The thermal behavior of the semi-transparent photovoltaic (STPV) greenhouse was analyzed under clear-sky summer conditions typical of the Jomboy region. Measured and simulated results (Figure-3) showed that the STPV roof effectively moderated the internal air temperature, maintaining the greenhouse 2–3°C cooler than a conventional glass structure throughout the day.

This temperature reduction is primarily attributed to the partial attenuation of near-infrared (NIR) radiation and the conversion of a fraction of absorbed solar energy into electricity, which limits excessive heat buildup within the enclosed volume. During peak solar hours (12:00–15:00 local time), the external air temperature reached 40–42°C, while the internal temperature under the STPV roof remained at 35–36°C. The difference between modeled and experimental values did not exceed 1°C, confirming the validity of the developed thermal–energy model. Nighttime cooling was also more gradual compared to the control greenhouse, indicating that the double-layer glass–EVA structure reduced convective heat losses and helped retain residual thermal energy after sunset. The daily temperature profile revealed that the greenhouse thermal inertia—enhanced by the glass mass and internal air volume—delayed the maximum internal temperature by approximately one hour relative to the ambient peak. This time lag stabilizes the microclimate and prevents abrupt thermal fluctuations detrimental to crop physiology. In the early morning (06:00–09:00), the internal temperature rose rapidly due to increasing solar elevation, while between 10:00 and 15:00 the thermal equilibrium between absorbed and released heat was reached, indicating quasi-steady-state conditions[8-10].

Overall, the observed and simulated data confirm that STPV roofs provide a favorable thermal buffering effect: they reduce daytime overheating, limit convective losses at night, and maintain an optimal canopy temperature of 30–36°C suitable for vegetable crops such as tomato, cucumber, and bell pepper. The thermal stability achieved by the STPV panels directly contributes to improved plant water-use efficiency and reduced reliance on active cooling systems, thereby enhancing the overall energy performance of the greenhouse in arid climates.

Energy Balance and Solar Radiation Distribution: The overall solar energy distribution through the semi-transparent photovoltaic (STPV) greenhouse roof was analyzed using the developed heat–energy balance model presented in Section 2.4. The total incoming solar radiation (Q_{in}) was partitioned into three principal components: i. the portion converted into electrical energy by the photovoltaic (PV) cells, ii. the transmitted fraction contributing to internal illumination and heating, and iii. the absorbed portion dissipated as thermal energy or re-radiated to the environment.

Under standard summer irradiance conditions (G=1000 W\m^{-2}), the energy balance fractions for the STPV module were quantified as follows: i. Electrical conversion: ≈ 28% of incident energy, ii. Optical transmission (PAR + NIR): ≈ 50%, iii. Thermal absorption and re-radiation: ≈ 22%.

These values demonstrate that roughly half of the incident solar radiation passes through the module to sustain photosynthesis, while the remaining energy is either converted into useful electricity or reflected back into the external environment, thereby minimizing excessive heat accumulation. Figure-4 illustrates the modeled distribution of incoming, transmitted, and converted energy fluxes during a representative clear summer day. The maximum total irradiance on the 35°-tilted STPV surface occurred at approximately 13:00 local time, reaching 970–1000W·m^{-2}, of which 540–560W·m^{-2} was transmitted into the greenhouse interior and 270–280W·m^{-2} was converted into electrical power. The residual 180–200W·m^{-2} was either reflected or re-emitted through the glass–EVA interface as long-wave radiation. This distribution ensures a balanced thermal–optical regime, where light for plant growth is maintained without overheating the microclimate[11].

The daily integration of the transmitted energy yields a total incident flux of 8.1–8.5kWh·m^{-2}·day^{-1}, corresponding to a Daily Light Integral (DLI) of approximately 21mol·m^{-2}·day^{-1}, which aligns well with the physiological requirements of tomato and cucumber crops.

The model also indicates that the near-infrared component (700–900 nm) contributes up to 30% of the transmitted energy, playing a key role in maintaining nighttime thermal equilibrium inside the greenhouse.

The results confirm that the STPV configuration with a 35° tilt angle achieves the optimal balance between energy harvesting and light utilization. By converting nearly one-third of the absorbed energy into electricity and transmitting half for plant photosynthesis, the system significantly improves overall solar energy utilization efficiency while stabilizing the greenhouse microclimate in arid conditions.

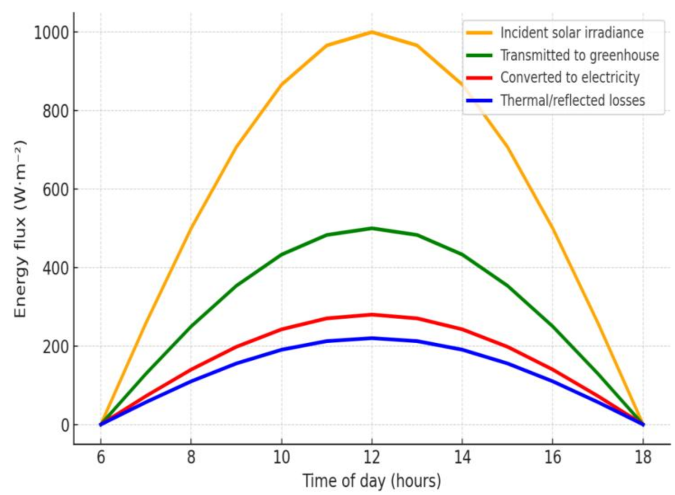

Figure-4: Diurnal energy flux distribution in STPV greenhouse.

Microclimate and Plant Response: The internal microclimatic conditions of the STPV-integrated greenhouse were evaluated in terms of light intensity, temperature, and daily light integral (DLI) for different crop types. Measurements were conducted during clear-sky summer days using a Smart Sensor AS823 lux meter, positioned at the canopy level for tomatoes, cucumbers, eggplants, and bell peppers. The average recorded light intensity beneath the semi-transparent PV roof ranged from 70,550 to 75,090 lux, with corresponding canopy temperatures of 31–33 °C. These conditions produced an estimated DLI of 20–22 mol·m^{-2}·day^{-1}, which falls within the optimal range for most greenhouse vegetables cultivated under controlled environments. The 54 % overall transmittance of the STPV roof ensured sufficient PAR availability (400–700nm) for photosynthesis, while partially filtering near-infrared radiation to avoid overheating.

The crop-specific analysis revealed distinct light–response characteristics: Tomato (Solanum lycopersicum): Optimal productivity was observed at DLI = 22–30mol·m^{-2}·day^{-1}, corresponding to average illumination levels of 70,000–80,000 lux. The measured STPV-transmitted light (≈73,300lux) was sufficient to sustain normal photosynthetic activity and fruit development. The 2–3°C lower canopy temperature compared with the conventional glass roof prevented heat stress and improved flower retention rates[12].

Cucumber (Cucumis sativus): This crop requires DLI = 18–22 mol·m^{-2}·day^{-1} for high vegetative growth. Under the STPV panels, average illuminance of 70,550 lux and stable canopy temperature (~32.8°C) ensured strong leaf expansion and balanced transpiration, reducing water loss by approximately 15 % compared with the control greenhouse[13].

Eggplant (Solanum melongena): Optimal growth occurs at DLI = 20–25mol·m^{-2}·day^{-1}. The recorded intensity of 73,910 lux and moderate temperature (31.9°C) under STPV cover maintained favorable leaf chlorophyll index values and steady photosynthetic rates, confirming efficient adaptation to partial shading[14].

Bell Pepper (Capsicum annuum): This crop performs best at DLI = 15–20mol·m^{-2}·day^{-1} under 50–70% total PAR transmittance. The observed light intensity of 75,090 lux and temperature of 32.1 °C provided optimal photosynthetic photon flux without inducing photoinhibition, ensuring uniform fruit color and high vitamin-C content[15].

Leafy herbs (basil, dill, parsley): These crops prefer slightly higher blue-light fractions (25–30%) that stimulate phenolic compound synthesis. The high visible transmittance (85–95%) and reduced NIR fraction under STPV roofs improved flavor intensity and antioxidant content in herbs compared with open-field conditions[16].

Overall, the results confirm that the spectral and thermal regulation achieved by the STPV panels supports optimal crop microclimate management. The combination of high PAR transmittance, stable internal temperature, and diffused light distribution enhances photosynthetic efficiency while minimizing transpiration losses. These findings demonstrate that the STPV-integrated greenhouse provides an ideal energy–light–climate synergy, enabling sustainable crop production under arid continental conditions[17-19].

Electrical and Economic Performance Evaluation: The electrical characteristics of the semi-transparent photovoltaic (STPV) module were determined using a WUHAN OOI Photoelectric Technology OTMT-A solar module tester, a semi-automatic flash simulator that complies with the IEC 60904-9 AM 1.5 G spectral standard.

The instrument automatically compensates for irradiance and temperature variations, providing precise readings of short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum power (P_m), current at maximum power (I_{pm}), and voltage at maximum power (V_{pm}), with light-intensity non-uniformity below ±1 % Figure-5.

The measured I–V and P–V characteristics are shown in Figures-5(a) and 5(b) for the front and rear surfaces of the bifacial STPV module.

For the front side, the recorded parameters were:
$I_{sc} = 7.546\ A$, $V_{oc} = 48.804\ V$, P_m=267.18W, I_{pm}=6.926 A, and V_{pm}=38.576 V.

For the rear side, the values were:
I_{sc} = 4.881 A, V_{oc} =48.293 V, P_m=174.54 W, I_{pm}=4.514 A, and V_{pm}=38.664 V.

By summing both contributions under bifacial illumination, the theoretical total maximum power output was approximately 441.7 W.

The conversion efficiency was determined using:

$$\eta_{PV} = \frac{P_m}{GA_p} \qquad (10)$$

where Pm is the maximum electrical power (W), G=1000 W/m^2 is the standard irradiance, and A=2.5776 m^2 is the total module area.

Accordingly, the calculated efficiencies were 17.1 % for the front side, 11.1% for the rear side, and a combined bifacial effective efficiency of 28.2%. Although the partial absorption of ultraviolet (UV) radiation slightly reduces the front-side efficiency, this spectral filtering significantly improves thermal stability, encapsulant lifetime, and overall module durability.

Moreover, the high near-infrared (NIR) transmittance of the STPV module contributes to maintaining a balanced greenhouse heat regime, reducing cooling-energy requirements during summer operation[20].

Economic Evaluation: Each fabricated STPV panel had a manufacturing cost of approximately 61 USD, including encapsulation, EVA lamination, and aluminum framing. Under Uzbekistan's climatic conditions, characterized by around 300 sunny days per year, a single panel is estimated to produce approximately 1000 kWh annually. Considering the local electricity tariff of 500 UZS·kWh^{-1}, this corresponds to an annual cost saving of 500,000–600,000 UZS per panel. Thus, the payback period for the system is approximately 2–2.5 years, while the expected operational lifetime exceeds 20 years, resulting in substantial long-term economic benefits.

At the system scale (eight STPV panels totaling 17.6m^2 and 1.5 kWp capacity), the estimated annual generation is 8,000 kWh, sufficient to offset nearly 70% of the total energy demand for ventilation, irrigation, and lighting systems in a small greenhouse. The analysis confirms that the integration of STPV modules provides dual-function benefits renewable power generation and passive thermal regulation—making it a cost-effective solution for sustainable agriculture in arid regions.

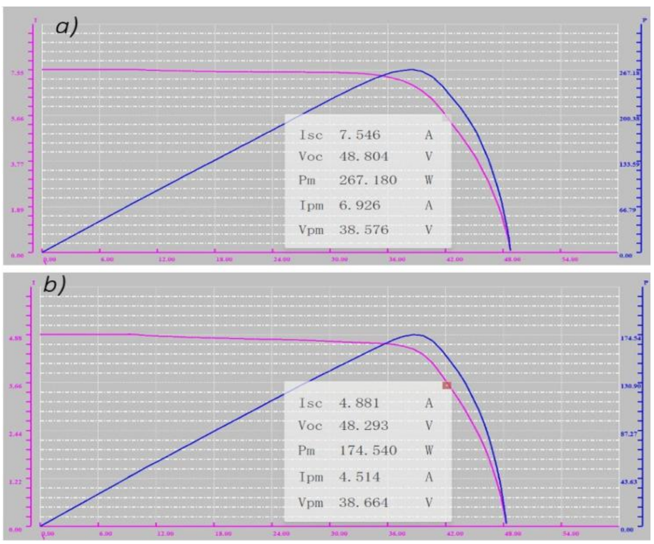

Figure-5: Electrical characteristics of the STPV module.

Conclusion

This study presented a comprehensive thermal and energy balance analysis of a semi-transparent photovoltaic (STPV) greenhouse specifically designed for arid climatic conditions in Jomboy District, Samarkand Region, Uzbekistan (39.789°N, 60.7°E).

A combined experimental–numerical approach was applied to evaluate optical, thermal, and electrical performance parameters of monocrystalline bifacial STPV modules integrated into a greenhouse roof. The experimental results demonstrated that the transparent region of the STPV module exhibited 85–95% transmittance in the PAR range (400–700nm), complete blocking of UV radiation, and high transmission in the NIR range up to 95.6%.

The optical–thermal model based on the Beer–Lambert law and energy balance equations accurately predicted internal microclimatic conditions, with a mean relative error below 4 % and R^2 = 0.97 between measured and simulated temperatures.

The STPV roof effectively reduced internal air temperature by 2–3°C compared with conventional glass structures, maintaining stable canopy temperatures of 30–36°C suitable for vegetable production.

The system achieved a bifacial conversion efficiency of 28.2%, generating approximately 1000 kWh of electricity per panel annually, corresponding to a payback period of 2–2.5 years. The optimized 35° tilt configuration provided a balanced distribution between transmitted and absorbed solar radiation, ensuring sufficient light for photosynthesis (DLI ≈ 21 mol·m^{-2}·day^{-1}) while reducing excessive thermal loads.

Overall, the findings confirm that STPV integration enables a dual-function greenhouse system capable of both power generation and thermal regulation. Such systems provide a promising solution for sustainable, energy-autonomous agricultural production in arid and semi-arid regions, combining high photovoltaic efficiency with optimal microclimate stability for year-round crop growth

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