

Temperature-Dependent Performance of FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au Dual-Absorber Perovskite Solar Cells: A SCAPS-1D Study

^{*1}Ejikeme Ezo Igbokwe, ²Tochukwu Ebere Esihe, ³Peter Uchechukwu Ndukwe and ²Henry Chima Chukwu



Department of Physics with Electronics, Ogbonnaya Onu Polytechnic, Aba, Abia State, Nigeria.

²Department of Chemistry/Biochemistry, Ogbonnaya Onu Polytechnic, Aba, Abia State, Nigeria.

³Department of Science Laboratory Technology, Federal Polytechnic Isuochi, Abia State, Nigeria.

*Corresponding author's email: ejikeme.igbokwe@ogbonnayaonupolytechnic.edu.ng

ABSTRACT

Perovskite solar cells have attracted significant attention because of their strong optical absorption, tuneable band gaps and favorable carrier-transport properties; however, their photovoltaic performance is strongly influenced by operating temperature. Understanding thermal sensitivity is therefore important for improving device stability and performance. In this study, the temperature-dependent photovoltaic behaviour of an FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell was investigated using SCAPS-1D version 3.3.12. The device was simulated from 300 to 400 K at 10 K intervals under AM1.5G illumination with an incident power density of 100 mW cm⁻². The effects of temperature on open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), power conversion efficiency (PCE), maximum-power voltage (V_{MPP}) and maximum-power current density (J_{MPP}) were evaluated, together with temperature-dependent carrier redistribution and recombination behaviour. At 300 K, the device exhibited V_{oc} = 0.9781 V, J_{sc} = 26.2441 mA cm⁻², FF = 82.93%, PCE = 21.29%, V_{MPP} = 0.8400 V and J_{MPP} = 25.3427 mA cm⁻². With increasing temperature, V_{oc} decreased to 0.8345 V at 400 K, whereas J_{sc} remained nearly constant at 26.24 mA cm⁻². FF reached a maximum of 83.76% at 340 K before declining to 81.61% at 400 K, while PCE decreased to 17.87%. Regression analysis of the simulated data yielded linear temperature coefficients of -1.437 mV K⁻¹ for V_{oc}, -1.88 × 10⁻⁶ mA cm⁻² K⁻¹ for J_{sc}, -0.0155 percentage points K⁻¹ for FF, and -0.0348 percentage points K⁻¹ for PCE. The results show that performance degradation at elevated temperatures is driven primarily by voltage and efficiency losses rather than photocurrent reduction, accompanied by carrier redistribution, modified spatial recombination profiles, and internal electric-field variation.

Keywords:

Perovskite solar cell,
Dual absorber,
CsPbI₂Br,
CsSnI₃,
Temperature dependence.

INTRODUCTION

The increasing demand for clean and sustainable electricity has intensified research into renewable-energy technologies, particularly solar photovoltaic (PV) systems. Recent reviews have highlighted the continuing development of different solar-cell technologies and the importance of absorber, transport-layer and device parameters in determining photovoltaic performance (Ho *et al.*, 2025). Among the available PV technologies, thin-film solar cells are attractive because of their potential for

low material consumption, lightweight structures and scalable fabrication (Ramanujam *et al.*, 2020). Continued improvement in photovoltaic performance therefore requires materials and device architectures that combine high conversion efficiency with appropriate stability and low-cost processing.

Perovskite solar cells have attracted considerable research interest because of their strong optical absorption, tunable band gaps and favorable carrier-transport properties (Kim *et al.*, 2020). These

characteristics enable efficient conversion of incident solar radiation and make perovskite materials promising candidates for high-performance thin-film photovoltaic devices. However, their photovoltaic characteristics are strongly dependent on operating temperature, making thermal effects an important consideration in device evaluation.

In practical operation, solar-cell temperatures can rise substantially above ambient temperature under solar irradiation. Temperature variations can modify carrier statistics, transport, recombination and the internal electrical characteristics of a device, thereby affecting key photovoltaic parameters such as open-circuit voltage, fill factor and power conversion efficiency (Green, 2003). Recent SCAPS-1D simulations of perovskite solar cells have demonstrated that temperature and defect-related processes can substantially influence photovoltaic performance and thermal losses (Igbokwe *et al.*, 2026a). The short-circuit current density (J_{sc}) may exhibit a different temperature response depending on the material properties and device architecture. Consequently, systematic temperature analysis is necessary for understanding the thermal behaviour of perovskite photovoltaic devices (Tang *et al.*, 2025).

CsPbI₂Br is an all-inorganic mixed-halide perovskite with a relatively wide band gap of approximately 1.88 eV in the present simulation (Xu, 2020). Its combination of a relatively wide band gap and favourable photovoltaic characteristics makes it attractive for advanced photovoltaic architectures (Igbokwe *et al.*, 2026d). However, its relatively wide band gap limits absorption of lower-energy, long-wavelength photons, creating an opportunity to combine it with a narrower-band-gap absorber.

CsSnI₃ provides such a complementary absorber because of its lower band gap of approximately 1.30 eV in the present device model. Its broader spectral absorption can complement the higher-band-gap CsPbI₂Br absorber and increase the range of solar radiation available for photogeneration. However, tin-based perovskites can also be influenced by defect states and carrier recombination, making the electronic interaction between the two absorber materials an important consideration (Zhang *et al.*, 2025).

The combination of CsPbI₂Br/CsSnI₃ therefore provides a dual-absorber configuration in which the two materials have different band gaps and can contribute to photon absorption over complementary spectral regions (Hasnain *et al.*, 2024). The resulting heterostructure provides two photoactive regions and introduces an absorber-absorber interface that can influence carrier distribution and recombination (Rahman *et al.*, 2025). In this study, the dual-absorber region is incorporated into the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au architecture, with SnO₂ and CuI serving as the electron- and hole-

transport layers, respectively. The device architecture and layer functions are defined in the present manuscript. Although temperature effects have been investigated for different perovskite solar-cell architectures, including recent SCAPS-1D studies of FASnI₃ devices over 300–400 K (Igbokwe *et al.*, 2026a), comparatively limited attention has been given to the temperature-dependent behaviour of dual-absorber devices combining CsPbI₂Br and CsSnI₃. In particular, the simultaneous evolution of photovoltaic parameters, maximum-power-point characteristics, carrier distributions and spatial recombination profiles over a broad temperature range warrants further numerical investigation.

Therefore, this study investigates the temperature dependence of the photovoltaic performance of an FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell using SCAPS-1D. The device is evaluated from 300 to 400 K under AM1.5G illumination at 100 mW cm⁻², with the effects of temperature on V_{oc} , J_{sc} , FF, PCE, V_{MPP} and J_{MPP} quantified. The study also examines carrier concentration, recombination and electric-field distributions to provide further insight into the simulated thermal response. The simulations use SCAPS-1D version 3.3.12.

MATERIALS AND METHODS

SCAPS-1D Simulation Software

The numerical simulations were performed using the Solar Cell Capacitance Simulator in one dimension (SCAPS-1D), version 3.3.12 (scaps3312.exe; dated 03-06-2025). The version is explicitly recorded in the validated SCAPS problem-definition file used for the simulations. SCAPS-1D was developed at the Department of Electronics and Information Systems (ELIS), University of Gent, Belgium, with contributions from researchers including Marc Burgelman and colleagues. The official SCAPS documentation describes the program as a one-dimensional solar-cell simulation tool capable of solving semiconductor transport and electrostatic problems, including bulk and interface defects, carrier generation and recombination, and photovoltaic characteristics.

SCAPS treats the solar cell as a one-dimensional multilayer semiconductor structure and numerically solves the coupled Poisson and electron/hole continuity equations together with the appropriate carrier-transport relations. The simulations account for electrostatic potential, carrier concentrations, generation, recombination, electric field and current transport throughout the device. SCAPS also permits the inclusion of bulk defect states, interface defects, temperature, illumination conditions and contact properties.

For the present study, SCAPS-1D version 3.3.12 was used consistently for the temperature-dependent

simulations. The problem-definition file confirms adaptive mesh calculation, with the maximum ratio between neighbouring mesh points set to 1.10 and the minimum ratio to 1.05 (Saidarsan *et al.*, 2024).

Device Architecture

The simulated device has the structure
FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au

Where FTO serves as the transparent front conducting electrode, SnO₂ functions as the electron-transport layer (ETL), CsPbI₂Br and CsSnI₃ constitute the dual-absorber region, CuI acts as the hole-transport layer (HTL), and Au serves as the back metallic electrode.

The two absorber layers are each 200 nm thick, as specified in the SCAPS definition file. SnO₂ and CuI are also specified as 200 nm layers.

The SnO₂ layer provides selective electron transport toward the FTO electrode, while CuI provides selective

hole transport toward the Au electrode (Murota *et al.*, 2022). The combination of the wider-band-gap CsPbI₂Br absorber and lower-band-gap CsSnI₃ absorber forms the dual-absorber photoactive region intended to enhance spectral utilization.

The FTO and Au layers were treated as electrical contacts rather than semiconductor layers. The front and back contact work functions were set to 5.20 and 4.40 eV, respectively, as specified in the validated SCAPS definition file. Both contacts were treated as fixed-work-function contacts (flatband condition not imposed), with tunnelling to the contacts disabled. The corresponding contact boundary conditions/barrier assumptions were retained as defined in SCAPS (Alali & Inanir, 2026). The Schematic representation of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar-cell structure is shown in Figure 1.

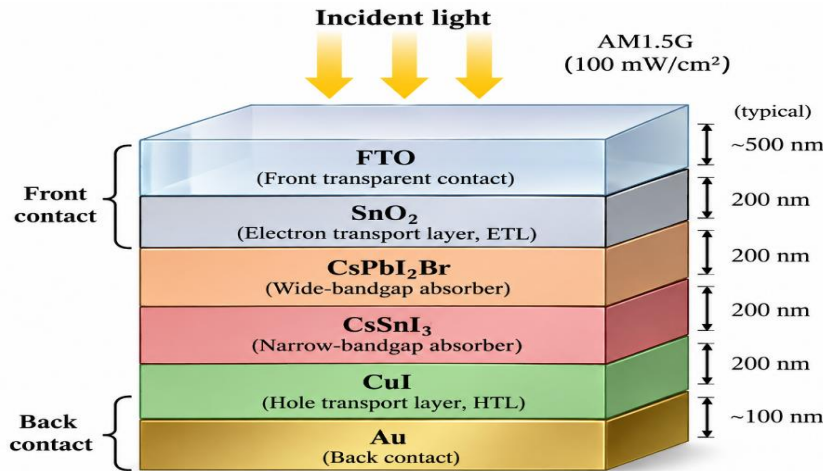


Figure 1. Schematic representation of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar-cell structure

Governing Equations

The electrical behaviour of the simulated device is described by the coupled semiconductor equations governing electrostatics and carrier transport. The principal equations are presented below.

Poisson Equation

$$\frac{d}{dx} \left(\epsilon \frac{d\psi}{dx} \right) = -q(p - n + N_D^+ - N_A^- \rho_{\text{def}}) \quad (1)$$

where ϵ is the permittivity, ψ is the electrostatic potential, q is the elementary charge, n and p are the electron and hole concentrations, N_D^+ and N_A^- are ionized donor and acceptor concentrations, and ρ_{def} represents the charge contribution associated with defect states.

Electron Continuity Equation

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} + G - R \quad (2)$$

where J_n is the electron current density, G is the carrier-generation rate and R is the total recombination rate.

Hole Continuity Equation

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} + G - R \quad (3)$$

where J_p is the hole current density.

Electron Current Density

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx} \quad (4)$$

Hole Current Density

$$J_p = q\mu_p p E - qD_p \frac{dp}{dx} \quad (5)$$

Where μ_n and μ_p are the electron and hole mobilities, respectively, D_n and D_p are the corresponding diffusion coefficients, and E is the electric field.

The electric field is related to the electrostatic potential by

$$E = -\frac{d\psi}{dx} \quad (6)$$

The generation term G represents photogenerated electron-hole pairs produced by absorption of incident photons. In the present simulations, optical generation was calculated internally by SCAPS under illumination (Hafidi *et al.*, 2026). SCAPS supports internal optical generation calculations based on absorption within the semiconductor layers.

The recombination term R accounts for carrier losses through the recombination mechanisms included in the SCAPS material definition. In the present parameter file, neutral Shockley-Read-Hall (SRH) defects were specified in the semiconductor layers. Defect-assisted SRH recombination is an important loss mechanism in tin-based perovskite solar cells and can strongly influence carrier lifetime and photovoltaic performance (Igbokwe *et al.*, 2026b).

In the material specifications, neutral Shockley-Read-Hall (SRH) defects were defined at a fixed energy level of 0.600 eV above the valence band in all four semiconductor layers (SnO₂, CsPbI₂Br, CsSnI₃, and CuI). This level should not be described as universally mid-gap because the four materials have different band gaps. The electron and hole capture cross-sections (σ_n and σ_p) were each set to $1.00 \times 10^{-15} \text{ cm}^2$. The corresponding thermal

velocities were $1.00 \times 10^7 \text{ cm s}^{-1}$ for both electrons and holes. The SRH energy distribution was material-dependent in the validated file: single-level for SnO₂ and CuI and Gaussian for CsPbI₂Br and CsSnI₃. SCAPS computes temperature-dependent semiconductor quantities such as intrinsic carrier concentration, thermal voltage, effective density of states, and carrier occupation using its internal semiconductor-statistics formulation. No additional empirical temperature coefficients for band gap or mobility were introduced in the present definition file.

The carrier mobilities and diffusion coefficients determine the drift and diffusion components of charge transport. The diffusion coefficients are related to the mobilities through the appropriate temperature-dependent Einstein relation (Jyegal, 2017). Defect-assisted recombination and transport limitations can significantly influence carrier collection and photovoltaic performance in perovskite devices (Igbokwe *et al.*, 2026c). Thus, changes in temperature influence carrier transport through both the thermal energy and the temperature-dependent semiconductor statistics incorporated by SCAPS.

Material and Device Parameters

The physical parameters used in the final SCAPS definition file are summarized in Table 1. All numerical values in the table were extracted from the validated SCAPS-1D problem-definition file. Values reported in the literature are used as supporting provenance where applicable, but literature values were not substituted for the actual inputs used in the present simulation. This distinction is important because published SCAPS studies can employ different effective densities of states, doping concentrations, mobilities, and defect densities.

Table 1: Physical Parameters of the Simulated Device Layers

Parameter	SnO ₂	CsPbI ₂ Br	CsSnI ₃	CuI	Provenance
Layer thickness (nm)	200	200	200	200	Validated SCAPS definition file
Band gap, E_g (eV)	3.60	1.88	1.30	2.98	SCAPS file; literature consistency (Dong <i>et al.</i> , 2024; Hossain <i>et al.</i> , 2023)
Electron affinity, χ (eV)	4.00	3.82	3.60	2.10	SCAPS file; literature consistency (Dong <i>et al.</i> , 2024; Hossain <i>et al.</i> , 2023)
Relative permittivity, ϵ_r	9.00	8.50	9.93	6.50	SCAPS file; literature consistency (Dong <i>et al.</i> , 2024; Hossain <i>et al.</i> , 2023)
Conduction-band effective DOS, N_C (cm ⁻³)	2.20×10^{18}	2.00×10^{18}	1.00×10^{19}	2.80×10^{19}	Validated SCAPS definition file
Valence-band effective DOS, N_V (cm ⁻³)	1.80×10^{19}	2.00×10^{18}	1.00×10^{18}	1.00×10^{19}	Validated SCAPS definition file

Parameter	SnO ₂	CsPbI ₂ Br	CsSnI ₃	CuI	Provenance
Electron mobility, μ_n (cm ² V ⁻¹ s ⁻¹)	100	20	1500	1	Validated SCAPS definition file
Hole mobility, μ_p (cm ² V ⁻¹ s ⁻¹)	10	20	585	20	Validated SCAPS definition file
Donor density, N_D (cm ⁻³)	1.00×10 ¹⁸	0	0	0	Validated SCAPS definition file
Acceptor density, N_A (cm ⁻³)	0	0	1.00×10 ¹⁹	1.00×10 ¹⁷	Validated SCAPS definition file
Bulk defect density, N_t (cm ⁻³)	1.00×10 ¹⁵	5.00×10 ¹⁴	5.00×10 ¹⁴	1.00×10 ¹⁴	Validated SCAPS definition file

Note. The numerical values were extracted directly from the validated SCAPS-1D problem-definition file. The original file stores carrier densities in m⁻³ and mobilities in m² V⁻¹ s⁻¹; these were converted to cm⁻³ and cm² V⁻¹ s⁻¹, respectively, for presentation. The bulk SRH defect densities are 1.00×10¹⁵, 5.00×10¹⁴, 5.00×10¹⁴, and 1.00×10¹⁴ cm⁻³ for SnO₂, CsPbI₂Br, CsSnI₃, and CuI, respectively. The FTO and Au layers were treated as electrical contacts and therefore are not assigned semiconductor-layer parameters. Dong *et al.* (2024) and Hossain *et al.* (2023) are cited as supporting literature for related material parameterizations, not as the direct source of every numerical value in the present model.

Interface Properties

The simulated device contains three semiconductor heterointerfaces: SnO₂/CsPbI₂Br, CsPbI₂Br/CsSnI₃ and CsSnI₃/CuI. No independent numerical interface-defect density, defect energy distribution or carrier-capture cross sections were assigned in the final simulation file. Therefore, the present study does not constitute a parametric investigation of interface-defect density. Recombination effects discussed in this work are associated primarily with the bulk defect states specified for the

assessment of operating-temperature effects on the photovoltaic response.

For the temperature analysis, illuminated current–voltage calculations were performed at each temperature, and the resulting V_{oc} , J_{sc} , FF, V_{MPP} , J_{MPP} , and PCE were recorded.

Photovoltaic Parameters

The photovoltaic performance was evaluated using the standard parameters extracted from the simulated current–voltage characteristics.

Open-circuit voltage

V_{oc}

Is the voltage at which the net current density is zero under illumination.

Short-circuit current density

J_{sc}

Is the current density at zero applied voltage.

Fill factor

$$FF = \frac{V_{MPP} J_{MPP}}{V_{oc} J_{sc}} \quad (7)$$

Power conversion efficiency

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{in} \times 100} \quad (8)$$

Here, V_{MPP} and J_{MPP} represent the voltage and current density at the maximum-power point, while P_{in} is the incident optical power density.

Temperature-Dependent Simulation Procedure

The temperature-dependent analysis was performed over $300 \leq T \leq 400$ K

With a temperature increment of

$\Delta T = 10$ K.

Thus, the simulated temperatures were 300, 310, 320, 330, 340, 350, 360, 370, 380, 390 and 400 K.

The incident illumination was maintained at

$P_{in} = 100$ mW cm⁻²

Using the AM1.5G, 1-sun spectrum. The SCAPS simulation file specifies internal optical generation, an AM1.5G spectrum and an incident power of 100 mW cm⁻². The temperature was varied as the batch parameter while the device architecture and material parameters were maintained. This procedure permits the isolated

Temperature Coefficient

The temperature coefficient of a photovoltaic parameter X was evaluated as

$$\beta_X = \frac{\Delta X}{\Delta T} \quad (8)$$

For example,

$$\beta_{V_{oc}} = \frac{\Delta V_{oc}}{\Delta T} \quad (9)$$

and

$$\beta_\eta = \frac{\Delta \eta}{\Delta T} \quad (10)$$

For parameters expressed as percentages, such as FF and PCE, the coefficients are reported in percentage points per kelvin to distinguish them from relative percentage changes.

The temperature coefficients of the key photovoltaic parameters were extracted using ordinary least-squares linear regression across all eleven simulated temperature data points from 300 K to 400 K. Specifically, each parameter was regressed against operating temperature to determine the slope, which defines the linear temperature coefficient. The regression slope quantifies the linear rate of change per unit temperature increase and was calculated for open-circuit voltage, short-circuit current density, fill factor, and power conversion efficiency to provide a consistent basis for comparative thermal sensitivity analysis.

RESULTS AND DISCUSSION

Baseline Photovoltaic Performance at 300 K

The photovoltaic performance of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber

device was first evaluated at 300 K under AM1.5G illumination with an incident power density of 100 mW cm⁻². The values shown in Table 2 are taken from the 300 K data point of the temperature sweep and serve as the reference against which the changes in photovoltaic performance from 300–400 K are evaluated. The simulated device exhibited a V_{oc} of 0.9781 V and J_{sc} of 26.2441 mA cm⁻², with a fill factor of 82.93% and a PCE of 21.2879%. The corresponding maximum-power point was $V_{MPP} = 0.8400$ V and $J_{MPP} = 25.3427$ mA cm⁻². These results establish the 300 K reference performance of the device for the subsequent temperature-dependent analysis. The relatively high FF indicates that the device maintains a strong maximum-power output under the simulated operating conditions.

Table 2: Baseline Photovoltaic Parameters of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au Device at 300 K

Photovoltaic parameter	Value at 300 K
V_{oc} (V)	0.9781
J_{sc} (mA cm ⁻²)	26.2441
FF (%)	82.9337
V_{MPP} (V)	0.8400
J_{MPP} (mA cm ⁻²)	25.3427
PCE (%)	21.2879

Effect of Temperature on J–V Characteristics

Figure 2 presents the simulated current-density–voltage (J–V) characteristics of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au solar cell over the temperature range of 300–400 K. Increasing temperature produces a progressive displacement of the J–V curves toward lower voltage, while the short-circuit current density remains almost unchanged. The voltage loss is therefore substantially larger than the corresponding change in photocurrent.

The maximum-power point follows the same trend, with (V_{MPP}) shifting from 0.840 V at 300 K to approximately 0.720 V at 400 K. In contrast, (J_{MPP}) changes only modestly over the same temperature interval. The FF remains close to 83% over much of the temperature range before decreasing at the highest temperatures. Consequently, the dominant visual feature of the J–V curves is the temperature-induced reduction in voltage rather than a substantial loss of current.

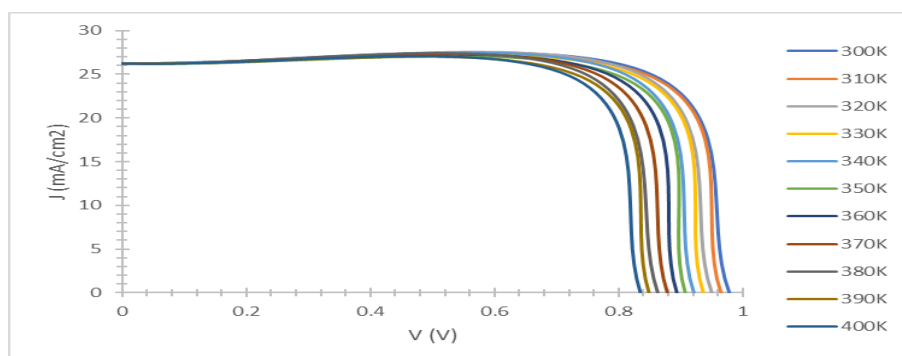


Figure 2: Simulated current-density–voltage (J–V) characteristics of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell at temperatures ranging from 300 to 400 K

Effect of Temperature on Open-Circuit Voltage

Figure 3 shows the temperature dependence of (V_{oc}). The SCAPS-1D results exhibit an approximately linear decrease in (V_{oc}) with increasing temperature. Based on the endpoint values, (V_{oc}) decreases from 0.9781 V at 300 K to 0.8345 V at 400 K. The corresponding endpoint temperature coefficient is approximately

The average temperature coefficient obtained from the end-point values is

$$\beta_{V_{oc}} = \frac{V_{oc}(400) - V_{oc}(300)}{400 - 300}$$

$$\beta_{V_{oc}} = \frac{0.8345 - 0.9781}{100} \approx -1.44 \times 10^{-3} \text{ V K}^{-1},$$

or approximately

$$\beta_{V_{oc}} \approx -1.44 \text{ mV K}^{-1}.$$

The decrease in (V_{oc}) is consistent with the temperature dependence of the semiconductor saturation current and thermally activated recombination processes. As temperature increases, enhanced carrier recombination

and the associated increase in the effective dark current reduce the voltage that can be sustained under open-circuit conditions. The magnitude of the simulated coefficient therefore identifies (V_{oc}) as the principal electrical parameter responsible for the thermal sensitivity of the device.

This behavior is broadly consistent with previous studies of perovskite photovoltaic devices. Moot *et al.* (2021), for example, demonstrated that perovskite photovoltaic devices exhibit measurable temperature coefficients in their electrical output and emphasized the importance of these coefficients for realistic energy-yield calculations. Similarly, Green (2003) established the general physical basis for the temperature dependence of solar-cell voltage. The present dual-absorber device therefore follows the expected qualitative behavior, although the magnitude of the coefficient is specific to the simulated material combination, layer parameters, defect assumptions, and operating conditions.

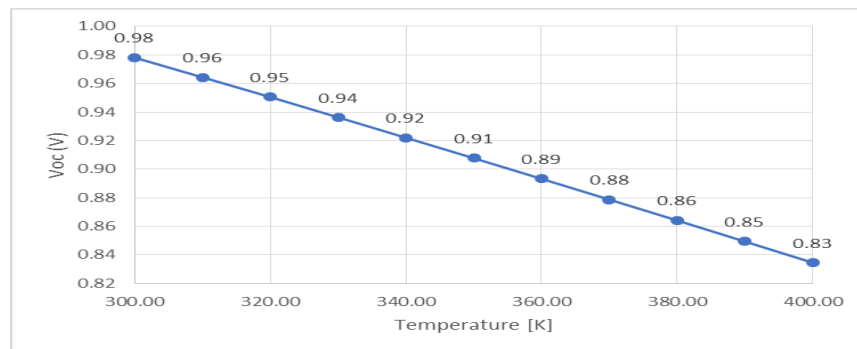


Figure 3: Temperature dependence of the open-circuit voltage (V_{oc}) of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell obtained from SCAPS-1D simulation over the temperature range of 300–400 K.

Effect of Temperature on Short-Circuit Current Density

Figure 4 presents the temperature dependence of (J_{sc}). The simulated value remains essentially unchanged throughout the investigated range, changing from 26.2441 mA cm⁻² at 300 K to 26.2439 mA cm⁻² at 400 K. Using the displayed endpoint values gives an approximate coefficient of

$$\beta_{J_{sc}} = \frac{26.243948 - 26.244141}{400 - 300} \approx -1.93 \times 10^{-6} \text{ mA cm}^{-2} \text{ K}^{-1}.$$

Thus, within the numerical precision of the reported results, (J_{sc}) is effectively temperature-independent over 300–400 K.

The nearly constant photocurrent indicates that the optical generation and net carrier extraction predicted by the SCAPS model are comparatively insensitive to temperature under the specified AM1.5G illumination. This does not imply that individual microscopic quantities such as mobility or recombination are temperature-independent; rather, their combined influence does not produce an appreciable change in the extracted short-circuit current within the present model. Accordingly, the temperature-induced deterioration in the overall photovoltaic performance cannot be attributed primarily to a loss of (J_{sc}). Instead, the dominant degradation arises from voltage loss, with a smaller contribution from the change in FF.

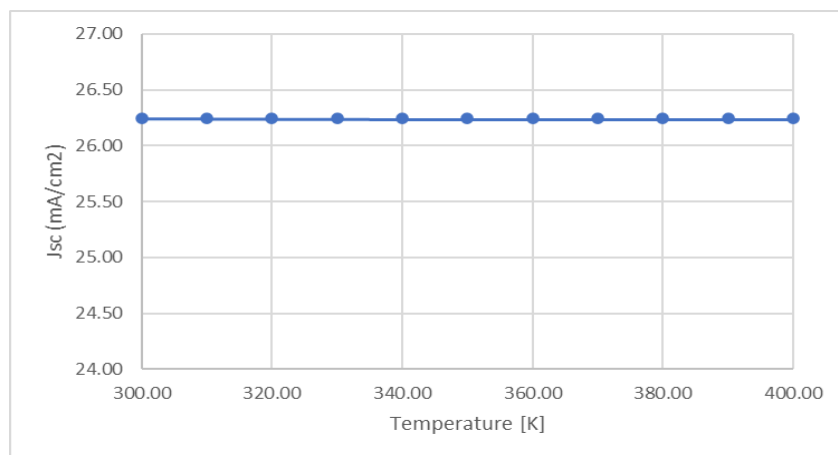


Figure 4: Variation of short-circuit current density (J_{sc}) with temperature for the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell simulated using SCAPS-1D over the temperature range of 300–400 K

Effect of Temperature on Fill Factor

Figure 5 shows the temperature dependence of the FF. The FF increases slightly from 82.93% at 300 K to a maximum of approximately 83.76% at 340 K before decreasing to approximately 81.61% at 400 K. The non-monotonic response indicates that the thermal influence on the shape of the J–V characteristic is relatively weak at moderate temperatures but becomes increasingly unfavorable at elevated temperature.

The initial increase may arise from the combined temperature dependence of carrier transport and recombination predicted by the model, whereas the subsequent decline indicates deterioration of the maximum-power operating condition at higher temperature. Because the SCAPS output used in this

study does not independently provide the temperature-dependent series and shunt resistances or quantitatively separate the individual recombination pathways, the FF variation should be interpreted as a combined device-level response rather than assigned to a single microscopic mechanism.

The magnitude of the FF change is considerably smaller than the voltage change. This distinction is important because it indicates that the thermal degradation of the present device is primarily voltage-driven, with FF acting as a secondary contributor. Temperature-dependent FF behavior has also been reported for perovskite photovoltaic devices, where changes in recombination and transport influence the shape of the J–V characteristic (Moot *et al.*, 2021).

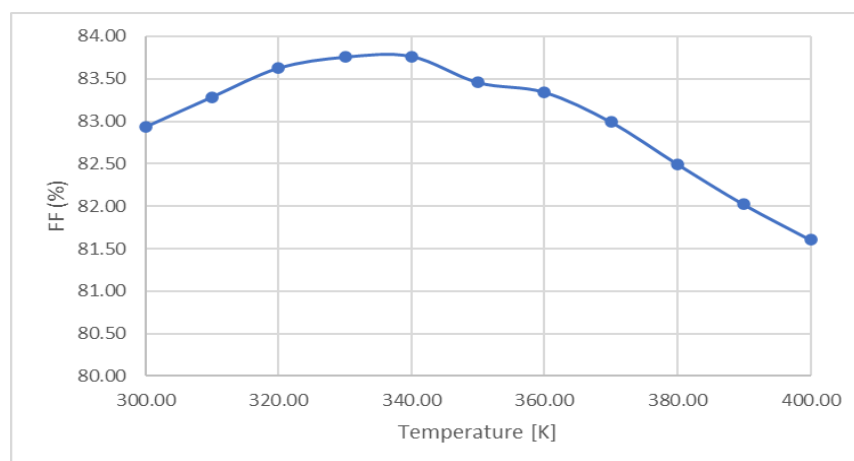


Figure 5: Effect of temperature on the fill factor (FF) of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell obtained from SCAPS-1D simulation over the temperature range of 300–400 K.

Effect of Temperature on Power Conversion Efficiency

Figure 6 summarizes the resulting PCE response. The efficiency decreases from 21.2879% at 300 K to approximately 17.87% at 400 K, corresponding to an overall relative reduction of approximately 16.05%. Linear fitting of the simulated data gives an efficiency temperature coefficient of approximately -0.0348 percentage points K^{-1} , equivalent to approximately -0.348 percentage points per 10 K.

The decrease in PCE results from the combined temperature dependence of (V_{oc}), FF, and, to a much smaller extent, (J_{sc}). However, because (J_{sc}) is essentially invariant while (V_{oc}) undergoes a

substantially larger change, the voltage loss represents the dominant contribution to the efficiency degradation. The slight decline in FF at elevated temperature further reduces the maximum extractable power.

The calculated PCE response is therefore consistent with the device-level behavior observed in Figures 2–5: increasing temperature primarily reduces the voltage operating window and consequently lowers the maximum electrical power available from the device. For practical operation, therefore, thermal management and temperature control are important for maintaining high PCE, particularly under conditions where the cell temperature approaches 400 K (Wen, 2026).

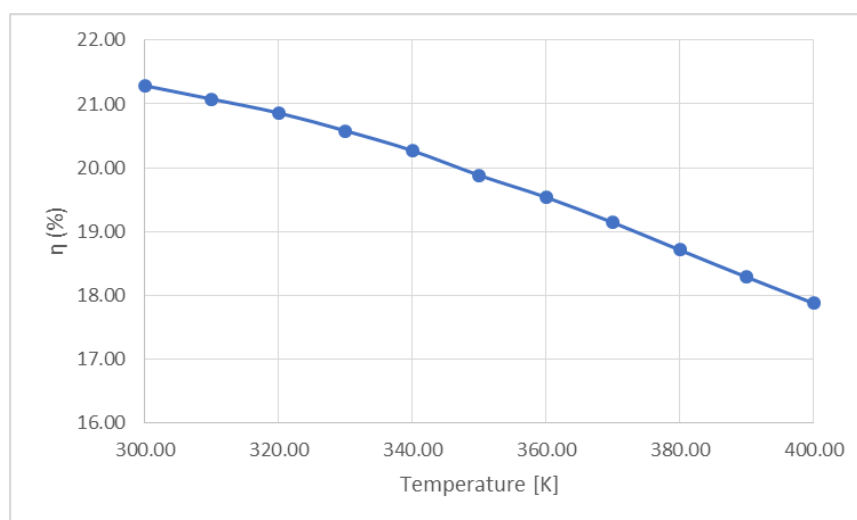


Figure 6: Variation of power conversion efficiency (η) with temperature for the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell obtained from SCAPS-1D simulation over the temperature range of 300–400 K.

Temperature Dependence of Maximum Power Parameters

Figure 7 presents the temperature dependence of (V_{MPP}) and (J_{MPP}). (V_{MPP}) decreases progressively from 0.840 V at 300 K to approximately 0.720 V at 400 K, corresponding to an endpoint reduction of approximately 14.3%. This behavior follows the reduction in (V_{oc}) and indicates that the optimum operating voltage moves toward lower values as the cell temperature increases.

By comparison, (J_{MPP}) exhibits only a modest and non-monotonic variation over the temperature range, with values between approximately 24.71 and 25.44 $mA\ cm^{-2}$.

The endpoint values decrease from 25.34 $mA\ cm^{-2}$ at 300 K to approximately 24.82 $mA\ cm^{-2}$ at 400 K. Thus, the temperature-induced displacement of the maximum-power point is dominated by the reduction in operating voltage rather than by a substantial change in current.

This result is consistent with analytical treatments of temperature-dependent maximum-power-point behavior, which identify the voltage coordinate of the maximum-power point as particularly sensitive to temperature (Garcia *et al.*, 2022). For the present device, the practical implication is that maximum-power tracking would need to accommodate a progressively lower operating voltage as the cell temperature increases.

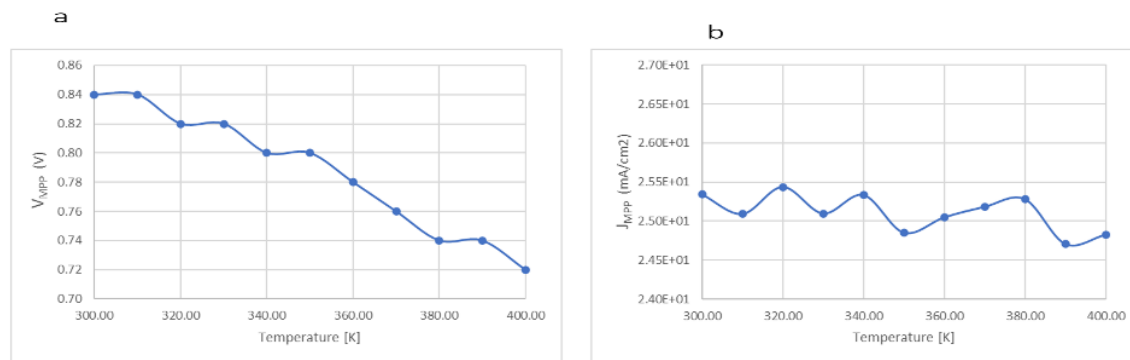


Figure 7: Temperature dependence of (a) maximum-power voltage (V_{MPP}) and (b) maximum-power current density (J_{MPP}) of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber perovskite solar cell obtained from SCAPS-1D simulation over 300–400 K.

Temperature Coefficients of Photovoltaic Parameters

The temperature coefficients calculated from the 300–400 K SCAPS-1D temperature sweep are summarized in Table 3. The coefficients describe the change in each photovoltaic parameter per kelvin and were obtained from the linear temperature dependence of the simulated

data. For (V_{OC}) and (J_{SC}), the coefficients are expressed in $V K^{-1}$ or $mA cm^{-2} K^{-1}$, respectively, whereas FF and PCE are expressed in percentage points K^{-1} (Cotfas *et al.*, 2018). The coefficient of determination (R^2) is also reported to quantify the goodness of fit of the linear regression over the investigated temperature range.

Table 3: Temperature Coefficients and Coefficients of Determination of Photovoltaic Parameters of the Simulated Dual-absorber Device

Parameter	Temperature coefficient	R^2
V_{oc}	-1.437 mV K^{-1}	0.988
J_{sc}	$-1.88 \times 10^{-6} \text{ mA cm}^{-2} \text{ K}^{-1}$	1.000
FF	$-0.0155 \% \text{ K}^{-1}$	0.789
PCE (η)	$-0.0348 \% \text{ K}^{-1}$	0.517

The regression results indicate that (V_{OC}) exhibits a strong and approximately linear temperature dependence, as reflected by its relatively high (R^2) value of 0.988. In contrast, (J_{SC}) shows an almost perfectly linear but essentially invariant response over the investigated temperature range, with ($R^2 = 1.000$). The lower (R^2) values obtained for FF (0.789) and PCE (0.517) indicate greater departures from a strictly linear temperature response. This is consistent with the non-monotonic variation of FF, which initially increases before declining at elevated temperatures, and with the cumulative influence of (V_{OC}), FF and (J_{SC}) on PCE. Thus, the (R^2) values should be interpreted as measures of the adequacy of a linear representation of the simulated temperature response rather than as indicators of photovoltaic performance or device quality.

Among the investigated parameters, (V_{OC}) exhibits the largest temperature sensitivity in terms of its absolute electrical temperature coefficient, whereas (J_{SC}) is effectively insensitive to temperature over the investigated interval. The FF and PCE show intermediate

temperature dependence, with the PCE response reflecting the combined effects of voltage, fill factor and photocurrent. The substantially smaller magnitude of the (J_{SC}) coefficient compared with that of (V_{OC}) indicates that the reduction in photovoltaic performance with increasing temperature is dominated by voltage loss rather than by a significant reduction in photocurrent.

Published studies of perovskite photovoltaic devices have similarly demonstrated measurable temperature dependence of photovoltaic output, although the magnitude of the temperature coefficients varies with absorber composition, device architecture, transport layers, defect properties, measurement conditions and temperature range. Moot *et al.* (2021) reported that temperature coefficients are an important consideration in estimating the energy yield of perovskite photovoltaic technologies and that their magnitude differs among device configurations. Cotfas *et al.* (2018) likewise demonstrated that (V_{OC}), (J_{SC}), FF and efficiency can exhibit different temperature sensitivities. Green (2003) established the broader theoretical basis for the strong

temperature dependence of solar-cell voltage through the temperature dependence of semiconductor carrier statistics and recombination processes. The present coefficients should therefore be regarded as device-specific values obtained from the specified SCAPS-1D model rather than as universal temperature coefficients for CsPbI₂Br/CsSnI₃ perovskite solar cells.

A relevant distinction is that the present architecture combines CsPbI₂Br and CsSnI₃ as dual absorbers, whereas several published temperature studies have considered single-absorber perovskite devices or different device architectures. Consequently, direct numerical comparison should be made cautiously because differences in absorber band gap, transport-layer properties, defect densities, contact conditions and simulation or experimental procedures can substantially affect the resulting coefficients. Nevertheless, the present results share the principal qualitative feature reported in the literature: increasing temperature produces a considerably stronger change in photovoltaic voltage than in short-circuit current. The present simulation therefore indicates that voltage degradation is the principal contributor to the reduction in PCE over 300–400 K, while the photocurrent remains comparatively stable.

Recombination and Carrier Transport Analysis

The energy-band simulation file was used to examine the spatial distributions of electron concentration (*n*), hole concentration (*p*), recombination, generation, total current density (*J*_{tot}), and electric field (*E*) at temperatures between 300 and 400 K. The analysis shows that temperature produces a redistribution of carriers and electric field within the dual-absorber structure rather than a uniform increase in all carrier-related quantities.

The electron and hole concentration profiles shown in Figure 8 at selected temperatures (300, 350 and 400 K) show appreciable temperature-dependent redistribution of carriers across the absorber layers. At the CsPbI₂Br/CsSnI₃ interface (approximately *x* = 0.40 μm), the simulated electron concentration changes from approximately $1.87 \times 10^{11} \text{ cm}^{-3}$ at 300 K to $1.82 \times 10^{11} \text{ cm}^{-3}$ at 350 K and $3.58 \times 10^{10} \text{ cm}^{-3}$ at 400 K. The corresponding hole concentration increases substantially, from approximately $1.28 \times 10^{10} \text{ cm}^{-3}$ at 300 K to $8.77 \times 10^{10} \text{ cm}^{-3}$ at 350 K and $1.39 \times 10^{14} \text{ cm}^{-3}$ at 400 K.

These results indicate that increasing temperature modifies the carrier distribution and the local electron–hole balance, particularly near the absorber junction. The profiles therefore provide evidence of temperature-dependent carrier redistribution within the dual-absorber region.

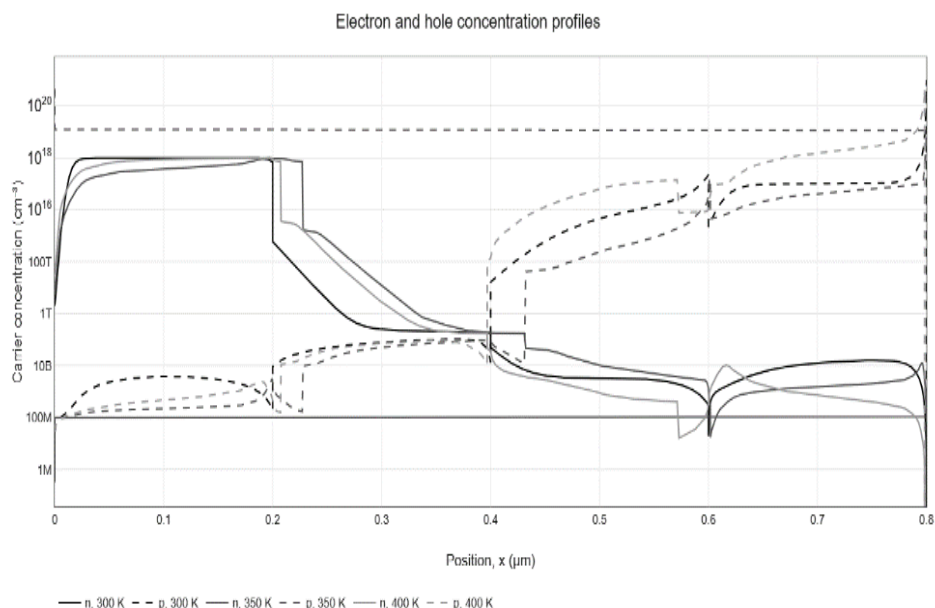


Figure 8: Electron and hole concentration profiles of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber solar cell at selected temperatures of 300, 350 and 400 K obtained from SCAPS-1D.

The recombination profiles presented in Figure 9 show that recombination is spatially non-uniform and develops pronounced peaks within the absorber region. At the CsPbI₂Br/CsSnI₃ interface, the recombination rate is approximately $5.88 \times 10^{16} \text{ cm}^{-3}\text{s}^{-1}$ at 300 K, increases $2.88 \times 10^{17} \text{ cm}^{-3}\text{s}^{-1}$ at 350 K, and is $2.06 \times 10^{17} \text{ cm}^{-3}\text{s}^{-1}$ at 400 K.

Importantly, the file does **not** show a monotonic increase in recombination at the interface with temperature. Moreover, the maximum recombination rate occurs slightly inside the absorber region rather than exactly at the CsPbI₂Br/CsSnI₃ boundary: approximately $3.42 \times 10^{17} \text{ cm}^{-3}\text{s}^{-1}$ at 300 K, $3.30 \times 10^{17} \text{ cm}^{-3}\text{s}^{-1}$ at 350 K, and $3.69 \times 10^{17} \text{ cm}^{-3}\text{s}^{-1}$ at 400 K. Therefore, the simulation supports temperature-dependent recombination and carrier redistribution, but it does not

justify stating that the CsPbI₂Br/CsSnI₃ interface itself is the dominant recombination site.

The generation rate remains comparatively high, with a maximum of approximately $8.73 \times 10^{21} \text{ cm}^{-3}\text{s}^{-1}$, while the total current density remains close to 26.24 mA/cm^2 across the temperature range. The electric field at the CsPbI₂Br/CsSnI₃ interface decreases from approximately $2.72 \times 10^4 \text{ V/cm}$ at 300 K to $2.13 \times 10^4 \text{ V/cm}$ at 400 K, indicating a temperature-dependent modification of the internal electrostatic field.

Overall, the results indicate that temperature primarily alters carrier redistribution, local recombination, and the internal electric-field profile, while the generated and extracted photocurrent remains comparatively stable (Hafidi *et al.*, 2026). This behavior is consistent with the previously observed temperature-induced reduction in V_{oc} and PCE.

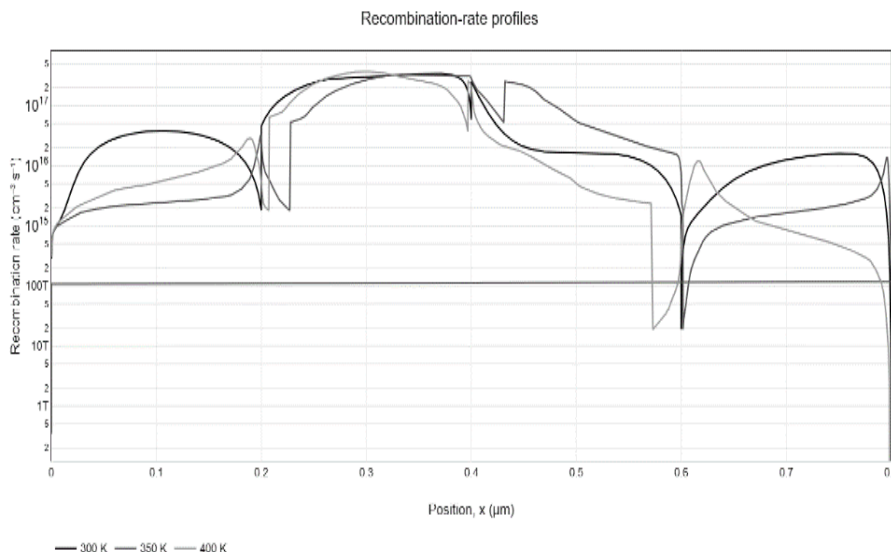


Figure 9: Recombination-rate profiles of the FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber solar cell at selected temperatures of 300, 350 and 400 K obtained from SCAPS-1D

CONCLUSION

This study investigated the temperature-dependent performance of an FTO/SnO₂/CsPbI₂Br/CsSnI₃/CuI/Au dual-absorber solar cell using SCAPS-1D from 300 to 400 K. At 300 K, the device achieved $V_{oc} = 0.9781 \text{ V}$, $J_{sc} = 26.2441 \text{ mA cm}^{-2}$, $FF = 82.93\%$, $PCE = 21.29\%$, $V_{MPP} = 0.8400 \text{ V}$, and $J_{MPP} = 25.3427 \text{ mA cm}^{-2}$.

Increasing temperature to 400 K reduced V_{oc} to 0.8345 V and PCE to 17.87% , while J_{sc} remained nearly constant at $\sim 26.24 \text{ mA cm}^{-2}$. The FF peaked at 83.76% (340 K) before declining to 81.61% at 400 K, demonstrating that thermal losses are voltage-driven.

Linear regression yielded temperature coefficients of -1.437 mV K^{-1} for V_{oc} , $-1.88 \times 10^{-6} \text{ mA cm}^{-2} \text{ K}^{-1}$ for J_{sc} , -0.0155% K^{-1} for FF, and -0.0348% K^{-1} for PCE. Carrier analysis confirmed temperature-dependent charge redistribution and internal field variations without indicating the heterojunction as the sole dominant recombination site.

These findings provide insights for optimizing dual-absorber architectures; however, as numerical predictions dependent on SCAPS input parameters, experimental validation is required.

REFERENCES

- Alali, A. S. A. I. T., & Inanir, F. (2026). Optimization of organic photodetector performance using SCAPS-1D simulation: Enhanced quantum efficiency and responsivity for UV detection. *Nanomaterials*, 16(5), 324. <https://doi.org/10.3390/nano16050324>
- Cotfas, D. T., Cotfas, P. A., & Machidon, O. (2018). Study of temperature coefficients for parameters of photovoltaic cells. *International Journal of Photoenergy*, 2018, 1–12. <https://doi.org/10.1155/2018/5945602>
- Dong, Y., Duan, J., Luo, D., Liu, J., Wang, X., Liu, X., & Gao, Y. (2024). Interface optimization of CsPbI₂Br based perovskite solar cells by device simulation. *Materials Today Communications*, 39, 108695.
- Garcia, A. S., Kristensen, S. T., & Strandberg, R. (2022). Analytical modeling of the temperature sensitivity of the maximum power point of solar cells. *IEEE Journal of Photovoltaics*, 12(5), 1237–1242. <https://doi.org/10.1109/JPHOTOV.2022.3178175>
- Green, M. A. (2003). General temperature dependence of solar cell performance and implications for device modelling. *Progress in Photovoltaics: Research and Applications*, 11(5), 333–340. <https://doi.org/10.1002/pip.496>
- Hafidi, E. M. E., Dimade, F., Amine, A., Chahid, A., Moznine, R. E., Tlemçani, M., & Laasri, S. (2026). SCAPS-1D simulation of lead-free CH₃NH₃SnBr₃ perovskite solar cells: Impact of temperature on photovoltaic and impedance performance. *Eng*, 7(8), 412. <https://doi.org/10.3390/eng7080412>
- Hasnain, S. M., Qasim, I., Iqbal, A., Mir, M. A., & Abu-Libdeh, N. (2024). Novel dual absorber configuration for eco-friendly perovskite solar cells: design, numerical investigations and performance of ITO-C60-MASnI₃-RbGeI₃-Cu₂O-Au. *Solar Energy*, 278, 112788.
- Ho, S., Igbokwe, E. E., & Olanmi, O. O. (2025). Photovoltaic technology: Power conversion efficiency of solar cells. *Asian Journal of Chemistry*, 37(9), 2092–2114.
- Hossain, M. K., Toki, G. I., Samajdar, D. P., Mushtaq, M., Rubel, M. H. K., Pandey, R., & Bencherif, H. (2023). Deep insights into the coupled optoelectronic and photovoltaic analysis of lead-free CsSnI₃ perovskite-based solar cell using DFT calculations and SCAPS-1D simulations. *ACS omega*, 8(25), 22466.
- Igbokwe, E. E., Nwaokorongwu, E. C., & Okpechi-Kanayochukwu, U. P. (2026a). Critical interface defect density governing thermodynamic losses and photovoltaic performance in FASnI₃ perovskite solar cells. *Nigerian Journal of Physics*, 35(S), [https://doi.org/10.62292/njp.v35\(s\).2026.732](https://doi.org/10.62292/njp.v35(s).2026.732)
- Igbokwe, E. E., Nwaokorongwu, E. C., Uchechukwu, A. K., & Emole, E. C. (2026b). Defect-dominated performance limits in FASnI₃ perovskite solar cells: A thickness-dependent simulation study. *Communication in Physical Sciences*, 13(5), 763–773. <https://doi.org/10.4314/cps.v13i5.7>
- Igbokwe, E. E., Nwaokorongwu, E. C., & Okpechi-Kanayochukwu, U. P. (2026c). Mechanistic investigation of interface defect density and electron capture cross-section on Shockley–Read–Hall recombination in FASnI₃ perovskite solar cells. *Journal of Chemical Society of Nigeria*, 51(4), 1009–1022. <https://doi.org/10.4314/jcsn.v51i4.20>
- Igbokwe, E. E., Nwaokorongwu, E. C., & Okpechi-Kanayochukwu, U. P. (2026d). Thickness-dependent optimization of CuI hole transport layer in CsPbI₂Br indoor perovskite solar cells: A SCAPS-1D study. *Journal of Chemical Society of Nigeria*, 51(4), 968–985. <https://doi.org/10.4314/jcsn.v51i4.18>
- Jyegal, J. (2017). Thermal energy diffusion incorporating generalized Einstein relation for degenerate semiconductors. *Applied Sciences*, 7(8), 773. <https://doi.org/10.3390/app7080773>
- Kim, J. Y., Lee, J. W., Jung, H. S., Shin, H., & Park, N. G. (2020). High-efficiency perovskite solar cells. *Chemical Reviews*, 120(15), 7867–7918. <https://doi.org/10.1021/acs.chemrev.0c00107>
- Moot, T., Johnston, S. W., McGehee, M. D., Wolf, E. J., Patel, J. B., Rosales, B. A., & Luther, J. M. (2021). Temperature coefficients of perovskite photovoltaics for energy yield calculations. *ACS Energy Letters*, 6(5), 2038–2047. <https://doi.org/10.1021/acsenenergylett.1c00748>
- Murota, A., Hayashi, R., Fujiwara, K., Nishida, T., Numata, Y., Oka, K., & Yamashita, K. (2022). Morphological and functional characterizations of SnO₂ electron extraction layer on transparent conductive oxides in lead-halide perovskite solar cells. *Applied Physics Letters*, 120(19), <https://doi.org/10.1063/5.0085559>
- Rahman, M. F., Rahman, M., Hossain, M. F., Islam, M. R., Islam, S., Ria, D. D., & Badi, N. (2025). Unraveling high-efficiency lead-free perovskite solar cells using a

- CsSnGeI₃/CsGeI₃ dual absorber and a Cu₂O HTL. *Scientific Reports*, 15(1), 42865.
- Ramanujam, J., Todorov, T. K., Rath, J. K., Bishop, D. M., Gunawan, O., Nekovei, R., & Arregiani, E. (2020). Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review. *Progress in Materials Science*, 110, 100619. <https://doi.org/10.1016/j.pmatsci.2019.100619>
- Saidarsan, A., Guruprasad, S., Malik, A. Q., Basumatary, P., & Ghosh, D. S. (2024). A critical review of unrealistic results in SCAPS-1D simulations: Causes, practical solutions and roadmap ahead. *Solar Energy Materials and Solar Cells*, 279, 113230. <https://doi.org/10.1016/j.solmat.2024.113230>
- Tang, Y., Liu, Y., & Li, M. (2025). Perspectives on various-temperature stability of p-i-n perovskite solar cells. *Applied Physics Letters*, 126(1). <https://doi.org/10.1063/5.0245576>
- Wen, T. (2026). Thermal management of photovoltaic modules: Material strategies and structural optimization. *Exploring Science Academic Conference Series*, 20, 86–91. <https://doi.org/10.70267/mseac.20268691>
- Xu, P. (2020). All-inorganic perovskite CsPbI₂Br as a promising photovoltaic absorber: A first-principles study. *Journal of Chemical Sciences*, 132(1). <https://doi.org/10.1007/s12039-020-01780-7>
- Zhang, J., Wang, J., Zhou, Q., Zhu, H., Pan, Y., Shi, C., & Chen, W. (2025). Dual-source defect managing of tin-lead perovskite for efficient all-perovskite tandem solar cells. *Advanced Functional Materials*, 35(8), 2415797.