

Numerical Assessment of Dust-Induced Photovoltaic Losses and Lotus-Inspired Self-Cleaning in $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ Perovskite Solar Cells

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ABSTRACT

Surface soiling can reduce the optical irradiance incident on photovoltaic absorbers and thereby lower energy yield. This study numerically evaluates the effects of dust-induced optical attenuation and operating temperature on a $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ perovskite solar cell using the Solar Cell Capacitance Simulator (SCAPS-1D). The simulated device employed a 500 nm CsPbI_2Br absorber between SnO_2 and CuI transport layers and was evaluated under AM1.5G illumination at 300–400 K. Surface contamination was represented by neutral-density optical transmission levels of 50–100%, corresponding to 50–0% modeled optical attenuation. A simplified self-cleaning model was introduced by assuming removal efficiencies of 30%, 50%, 70%, and 90% of the modeled deposited dust fraction. Temperature primarily affected the electrical parameters: V_{oc} decreased with temperature, whereas FF increased. In contrast, optical attenuation produced an approximately proportional reduction in J_{sc} and maximum power while causing comparatively small changes in V_{oc} and FF. At 300 K, reducing transmission from 100% to 50% reduced J_{sc} from 14.879 to 7.4395 mA cm^{-2} and reduced maximum power density from approximately 14.63 to 7.35 mW cm^{-2} . At 50% transmission, the modeled cleaning efficiencies of 30%, 50%, 70%, and 90% corresponded to approximately 65%, 75%, 85%, and 95% power retention, respectively. The results indicate that the modeled soiling loss is predominantly optical and that maintaining surface transmission can substantially mitigate the associated power loss. The model is a first-order representation of optical cleaning and requires experimental and wavelength-resolved validation.

Keywords:

Perovskite solar cells,
Dust Accumulation,
Self-Cleaning Surfaces,
SCAPS-1D.

INTRODUCTION

Perovskite solar cells (PSCs) have attracted sustained interest because their optical absorption, carrier-transport characteristics and tunable electronic structure support high photovoltaic performance. Progress in device engineering has increasingly emphasized the control of interfaces, transport layers and defect populations in addition to absorber composition (Ho et al., 2025; Jiang et al., 2019; Min et al., 2021). For all-inorganic mixed-halide systems such as CsPbI_2Br , appropriate selection of electron- and hole-transport layers is particularly important because interfacial charge extraction and recombination influence the final device output. Experimental work on $\text{SnO}_2/\text{CsPbI}_2\text{Br}$ devices has demonstrated the suitability of SnO_2 as an electron-

transport layer and the sensitivity of device performance to processing and interface quality (Gao et al., 2018). Although photovoltaic efficiency is often assessed under controlled laboratory illumination, outdoor devices operate under environmental conditions that modify the incident optical flux and the electrical properties of the cell. Surface soiling is one such factor. Deposited dust can scatter, absorb and reflect incident radiation, reducing the transmittance of the front surface. Measurements of photovoltaic soiling have shown that transmittance loss can be related to reductions in photovoltaic output and that the spectral characteristics of soiling can be important for different photovoltaic technologies (Micheli et al., 2019). Thus, the effect of dust should be distinguished from changes caused by temperature, recombination, transport and other intrinsic device processes.

Recent numerical work has further demonstrated the usefulness of optical-transmission models for quantifying photovoltaic soiling losses. Zhao et al. (2026), for example, developed theoretical transmittance models that relate dust deposition to optical attenuation while accounting for factors such as particle size, dust loading and solar incidence angle. Their results demonstrate that increasing dust deposition can substantially reduce module transmittance and consequently photovoltaic power output. Such approaches highlight the importance of distinguishing measured or modeled optical transmittance from geometric dust coverage. The present study adopts a deliberately simpler neutral-density representation so that the optical attenuation can be coupled directly to a semiconductor device model in SCAPS-1D.

Self-cleaning surfaces provide one possible route for reducing soiling losses. The lotus effect is based on hierarchical surface roughness combined with low surface energy, which promotes water repellence and facilitates removal of deposited particles. In photovoltaic applications, multifunctional self-cleaning surfaces have been investigated as a means of maintaining modeled optical attenuation while reducing maintenance requirements (Azad et al., 2024). However, a self-cleaning coating can only improve photovoltaic output indirectly: its principal function is to preserve the optical path to the active device rather than to modify the absorber's intrinsic electronic properties.

Numerical device simulation provides a practical way to isolate environmental effects from internal semiconductor processes. SCAPS-1D solves the coupled semiconductor equations governing electrostatic potential and carrier continuity and has been widely used for thin-film and perovskite solar-cell analysis (Burgelman et al., 2013). Recent SCAPS-based work has also shown that defect density and absorber thickness can strongly influence recombination and photovoltaic performance in perovskite devices (Igbokwe et al., 2026). Extending this type of device-level modeling to environmental optical attenuation can therefore help quantify the relationship between soiling and electrical output before experimental fabrication.

The present study addresses the gap between photovoltaic soiling and bioinspired self-cleaning by numerically coupling a dust-transmission model with a $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ device model. The objectives were to (i) quantify the effects of temperature and dust-induced optical attenuation on V_{oc} , J_{sc} , FF, PCE and maximum power output; (ii) establish which photovoltaic parameters are most sensitive to surface transmission loss; and (iii) estimate the power-retention benefit associated with different idealized lotus-inspired cleaning efficiencies. The study does not model the

micro/nanotopography or wetting dynamics of an actual lotus leaf; instead, it uses a transparent mathematical representation of dust removal.

MATERIALS AND METHODS

Device Structure and Simulation Environment

The photovoltaic device was simulated using the Solar Cell Capacitance Simulator (SCAPS-1D), version 3.3.12 (ELIS-UGent, Belgium; executable scaps3312.exe dated 3 June 2025). SCAPS-1D numerically solves Poisson's equation together with the electron and whole continuity equations to calculate carrier generation, transport and recombination in multilayer semiconductor devices (Burgelman et al., 2013). The modeled n-i-p structure was:

Front contact/ SnO_2 / CsPbI_2Br / CuI /Back contact

The front- and back-contact work functions were set to 5.2 and 4.4 eV, respectively. Electron and whole surface-recombination velocities were set to 1.0×10^5 and $1.0 \times 10^3 \text{ m s}^{-1}$ at the front contact and 1.0×10^3 and $1.0 \times 10^5 \text{ m s}^{-1}$ at the back contact, respectively. Tunnelling at contacts and interfaces was neglected. A series resistance of $1.0 \times 10^{-9} \Omega \text{ m}^2$ was included. Adaptive meshing was used with a maximum of ten mesh modifications per iteration step. The generation and recombination convergence limits were $1.0 \mu\text{A cm}^{-2}$ and $1.0 \times 10^{-3} \mu\text{A cm}^{-2}$, respectively.

Material Parameters

The SnO_2 electron-transport layer was assigned a thickness of 200 nm, bandgap of 3.60 eV, electron affinity of 4.00 eV, relative permittivity of 9.0, donor concentration of $1.0 \times 10^{24} \text{ m}^{-3}$, electron mobility of $1.0 \times 10^{-2} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ and hole mobility of $1.0 \times 10^{-3} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ based on reported SCAPS-1D material parameters for SnO_2 . (Biswas et al., 2023). The CsPbI_2Br absorber thickness was 500 nm, with a bandgap of 1.88 eV, electron affinity of 3.82 eV, dielectric constant of 8.5, electron and hole mobilities of $2.0 \times 10^{-3} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, and conduction- and valence-band effective densities of states of $2.0 \times 10^{24} \text{ m}^{-3}$. No intentional absorber doping was introduced. These parameters were adopted from reported CsPbI_2Br device-simulation studies and related perovskite parameter sets (Peng & Lin, 2025). The CuI hole-transport layer was 200 nm thick, with a bandgap of 2.98 eV, electron affinity of 2.10 eV, dielectric constant of 6.5, acceptor concentration of $1.0 \times 10^{23} \text{ m}^{-3}$, electron mobility of $1.0 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ and hole mobility of $2.0 \times 10^{-3} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ (Katunge et al., 2023; Banik et al., 2024). Parameters not directly available from the cited literature were selected as model assumptions for the present SCAPS simulation.

Table 1: Physical Parameters Used for the SCAPS-1D Simulation

Parameter	SnO ₂	CsPbI ₂ Br	CuI
Thickness (nm)	200	500	200
Bandgap, E _g (eV)	3.60	1.88	2.98
Electron affinity, χ (eV)	4.00	3.82	2.10
Dielectric constant	9.0	8.5	6.5
N _c (m ⁻³)	2.2×10^{24}	2.0×10^{24}	2.8×10^{25}
N _v (m ⁻³)	1.8×10^{25}	2.0×10^{24}	1.0×10^{25}
Electron mobility (m ² V ⁻¹ s ⁻¹)	1.0×10^{-2}	2.0×10^{-3}	1.0×10^{-4}
Hole mobility (m ² V ⁻¹ s ⁻¹)	1.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
Donor concentration, N _D (m ⁻³)	1.0×10^{24}	0	0
Acceptor concentration, N _A (m ⁻³)	0	0	1.0×10^{23}
Source	Biswas et al. (2023)	Peng & Lin (2025); Dong et al. (2024)	Katunge et al. (2023); Dong et al. (2024)

Note. Material parameters were selected from published literature and adapted where necessary for the present SCAPS-1D device model (Biswas et al., 2023; Katunge et al., 2023; Dong et al., 2024; Peng & Lin, 2025).

Defect and Interface Modeling

Shockley–Read–Hall recombination was included in all semiconductor layers. The bulk defect distribution was represented by a single neutral defect level located at 0.60 eV, with a characteristic energy of 0.10 eV. Electron and whole capture cross sections were both set to 1.0×10^{-19} m². The bulk defect densities were 1.0×10^{21} , 5.0×10^{20} , and 1.0×10^{20} m⁻³ for SnO₂, CsPbI₂Br, and CuI, respectively. Neutral interface defects were introduced at the SnO₂/CsPbI₂Br and CsPbI₂Br/CuI interfaces with an interface defect density of 1.0×10^{14} m⁻² and electron and hole capture cross sections of 1.0×10^{-23} m². These parameters were selected to provide a controlled representation of bulk and interfacial SRH recombination while allowing the environmental optical effects to be examined without simultaneously varying semiconductor defect properties.

Illumination and Temperature Conditions

All calculations used the standard AM1.5G one-sun spectrum supplied with SCAPS-1D at an incident power density of 100 mW cm⁻². Temperature conditions were 300, 325, 350, 375 and 400 K. At each condition, current-density–voltage characteristics were calculated and Voc, Jsc, FF, PCE, Vmpp and Jmpp were extracted.

The temperature range of 300–400 K was selected to examine the device response from near-standard laboratory conditions to elevated-temperature operation and thermal-stress conditions. The upper limit of 400 K (approximately 127 °C) should therefore be interpreted as an elevated-temperature sensitivity limit rather than as a representative continuous outdoor operating temperature. In the temperature sweep, the explicitly entered material parameters were kept fixed unless SCAPS internally treated the corresponding quantities as temperature dependent. In particular, the effective densities of states and carrier thermal velocities are temperature dependent in SCAPS, whereas the bandgap and mobility parameters used in the present model were not assigned explicit temperature-dependent laws. This treatment isolates the

temperature response arising from the simulator's built-in temperature dependence and the semiconductor transport/recombination equations.

Dust Accumulation Model

Dust deposition was represented by optical attenuation using the neutral-density (ND) filter transmission option in SCAPS-1D. Transmission levels of 50%, 60%, 70%, 80%, 90% and 100% were used. The corresponding modeled optical attenuation, D, was defined as:

$$D = 100 - T \quad (1)$$

Where D_{opt} is the modeled optical attenuation fraction expressed as a percentage, and T is the optical transmission percentage. Thus, $D_{\text{opt}} = 100 - T$ represents an effective optical attenuation parameter and should not be interpreted as a direct measurement of geometric surface coverage. Six transmission levels combined with five temperatures produced 30 simulation conditions.

Idealized Lotus-Inspired Optical-Cleaning Model

The potential effect of a lotus-inspired self-cleaning surface was represented by an idealized removal-efficiency model. Cleaning efficiencies of 30%, 50%, 70% and 90% were considered. The effective modeled optical attenuation was calculated as:

$$D_{\text{eff}} = D(1 - \eta_{\text{clean}}) \quad (2)$$

Where D_{eff} is the effective modeled optical attenuation after cleaning and η_{clean} is the cleaning efficiency expressed as a fraction. The maximum power density was calculated as:

$$P_{\text{MPP}} = V_{\text{MPP}} \times J_{\text{MPP}} \quad (3)$$

Power retention was then expressed as the ratio of power under the cleaned/dusty condition to the corresponding clean-surface reference power. This model is intentionally simplified and does not explicitly simulate surface roughness, contact angle, droplet dynamics, particle adhesion or wavelength-dependent scattering.

The term “lotus-inspired” is used here to describe the intended functional concept of maintaining surface cleanliness through passive removal of deposited particles. The mathematical model does not explicitly simulate lotus-leaf surface morphology, hierarchical roughness, contact-angle hysteresis, droplet motion, or particle adhesion. Instead, it represents the optical consequence of an assumed fractional removal of the dust.

Baseline Device Performance

Before the environmental simulations, the $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ device was evaluated under AM1.5G illumination at 300 K and 100% optical transmission (0% modeled optical attenuation). The baseline parameters obtained from the source simulation are presented in Table 2.

Table 2: Baseline Photovoltaic Performance of the $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ Device

Parameter	Value
Voc	1.48 V
Jsc	14.879 mA cm^{-2}
FF	66.21 %
PCE	14.49 %
Vmpp	1.040 V
Jmpp	13.94 mA cm^{-2}

Before the environmental simulations, the $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ device was evaluated under AM1.5G illumination at 300 K and 100% optical transmission. The resulting photovoltaic parameters are presented in Table 2. These values define the reference device state against which the effects of temperature and optical attenuation are evaluated. Because the present study is computational and does not include experimental measurements of the same device structure, the baseline calculation is treated as a reference simulation rather than as experimental validation. Previous numerical studies of $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ devices have reported comparable device architectures and photovoltaic parameters, supporting the relevance of the selected structure for parametric simulation.

RESULTS AND DISCUSSION

Temperature and dust effects on power conversion efficiency

Figure 1 presents PCE as a function of temperature for modeled optical attenuation levels of 50–100%. Across the simulated conditions, PCE increased from 300 K to approximately 375 K and then decreased slightly at 400 K. For the 100% transmission case, PCE increased from

about 14.60% at 300 K to 14.97% at 375 K before declining at 400 K. The similar temperature dependence of the transmission curves indicates that, within the modeled range, temperature has a stronger influence on PCE than the imposed broadband transmission loss.

The modest temperature-dependent increase up to 375 K is associated in the simulation with the competing effects of carrier transport and recombination. At higher temperature, the subsequent decline indicates that recombination and other thermally activated losses increasingly offset transport-related gains. In contrast, reducing transmission from 100% to 50% produced only a small change in PCE. Because the neutral-density filter attenuates the incident optical power used in the SCAPS calculation, PCE remains comparatively insensitive to broadband transmission loss when normalized to the attenuated incident power. Consequently, PCE alone does not adequately represent the absolute output-power penalty associated with soiling in this model. J_{sc} and maximum power density are therefore more appropriate indicators for quantifying the optical power loss introduced by the modeled attenuation.

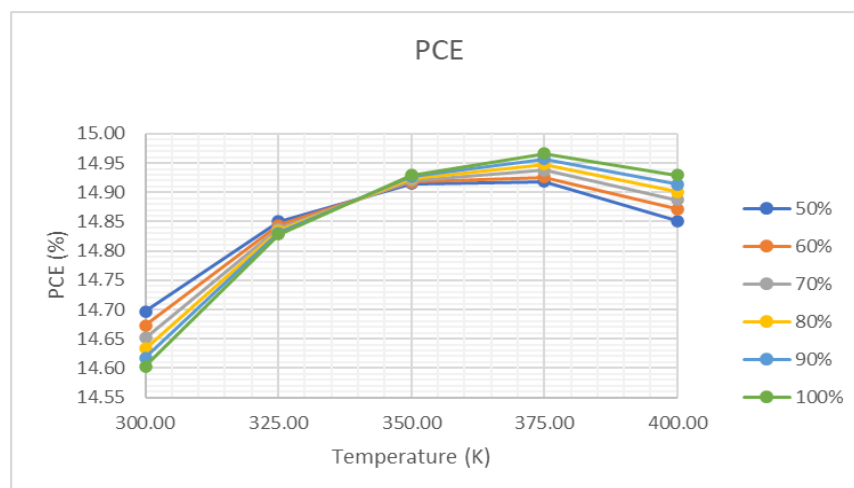


Figure 1: Effect of operating temperature and modeled optical attenuation on power conversion efficiency

Temperature and Dust Effects on Open-Circuit Voltage

As shown in Figure 2, V_{oc} decreased progressively from 300 to 400 K for all transmission levels. Under 100% transmission, V_{oc} decreased from approximately 1.48 V to 1.32 V, corresponding to a reduction of about 10.8%. This temperature response is consistent with increased thermally activated recombination and reduced quasi-Fermi-level splitting at elevated temperature.

Optical attenuation had a comparatively small effect on V_{oc} . At 300 K, reducing transmission from 100% to 50% lowered V_{oc} by approximately 0.03 V. The smaller sensitivity of V_{oc} compared with J_{sc} is consistent with the logarithmic dependence of photovoltage on photogenerated carrier concentration. Consequently, a self-cleaning surface is not expected to recover a large V_{oc} loss directly; its principal benefit is the preservation of incident photon flux.

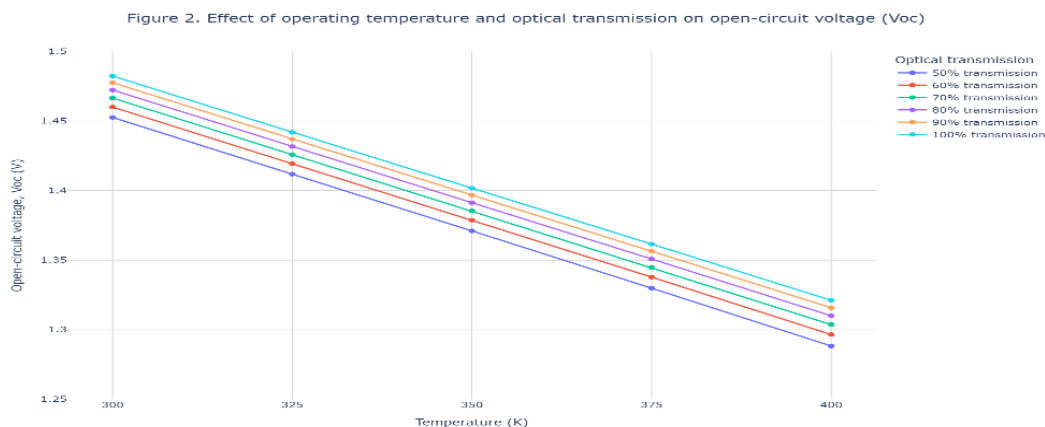


Figure 2: Effect of operating temperature and modeled optical attenuation on open-circuit voltage (V_{oc})

Temperature and Dust Effects on Short-Circuit Current Density

Figure 3 shows that J_{sc} was essentially insensitive to temperature over the investigated range but highly sensitive to modeled optical attenuation. Under 100% transmission, J_{sc} changed only slightly from 14.8790 mA cm^{-2} at 300 K to 14.8782 mA cm^{-2} at 400 K. In contrast, at 300 K, reducing transmission from 100% to 50% reduced J_{sc} from 14.8790 to 7.4395 mA cm^{-2} , an approximately 50% reduction.

The near-linear relationship between transmission and J_{sc} indicates that the principal mechanism represented by the dust model is optical attenuation. The semiconductor layers, defect parameters and transport properties were held constant while only the incident modeled optical attenuation was changed. Therefore, fewer transmitted photons produce fewer photogenerated carriers, leading directly to a lower short-circuit current. Among the photovoltaic parameters investigated, J_{sc} is consequently the clearest indicator of the modeled soiling loss.

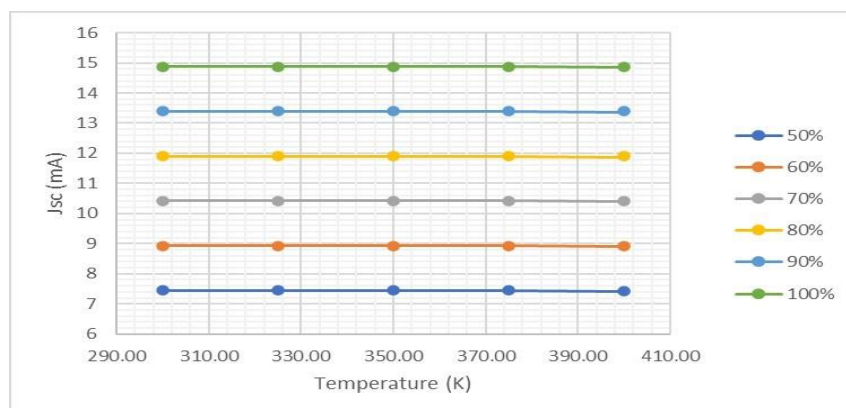


Figure 3: Effect of operating temperature and modeled optical attenuation on short-circuit current density (J_{sc})

Temperature and Dust Effects on Fill Factor

Figure 4 shows an increase in FF with temperature for all transmission levels. At 100% transmission, FF increased from approximately 66.2% at 300 K to 76.0% at 400 K. At 50% transmission, FF increased from approximately 68.0% to 77.5% over the same range. The close similarity among the transmission curves indicates that broadband attenuation did not strongly modify the modeled charge-extraction characteristics.

At 300 K, decreasing transmission from 100% to 50% produced only a small increase in FF. Thus, the principal effect of dust in this model is not a deterioration of the current-voltage curve shape but a reduction in the current available to the device. The opposing temperature trends of V_{oc} and FF also help explain the relatively modest variation in PCE across the temperature range.

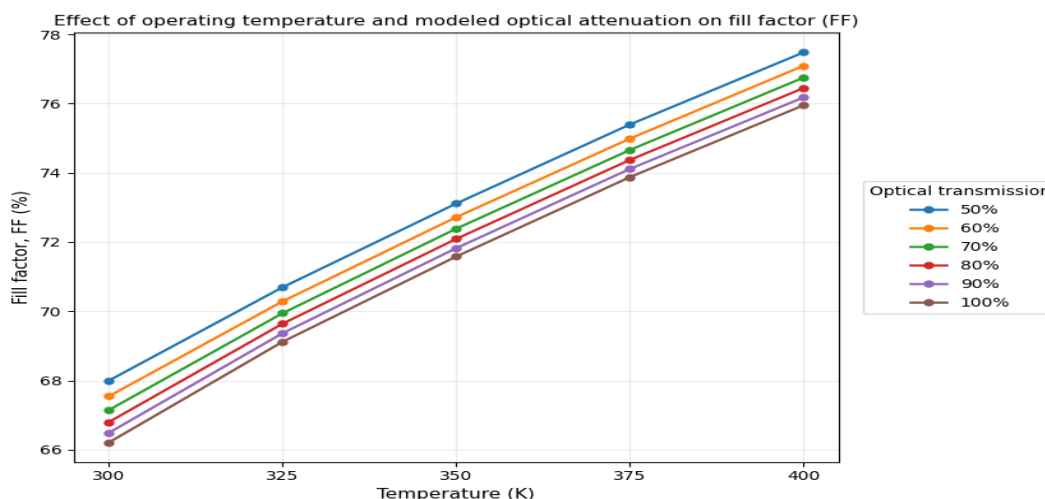


Figure 4: Effect of operating temperature and modeled optical attenuation on fill factor (FF)

Maximum Power Output under Dust-Induced Optical Attenuation

Maximum power density was calculated from Equation (3). Figure 5 shows that output power decreased almost linearly as modeled optical attenuation increase. At 300 K, the maximum power density decreased from approximately 14.63 mW cm^{-2} at 100% transmission to approximately 7.35 mW cm^{-2} at 50% transmission, corresponding to nearly 50% power loss.

The strong response of maximum power to transmission, despite comparatively small changes in V_{oc} and FF, confirms that the simulated soiling loss is primarily photocurrent-limited. This result is consistent with the established relationship between optical transmittance and photovoltaic soiling losses (Micheli et al., 2019). It also provides a direct physical basis for evaluating self-cleaning surfaces: maintaining transmission should preserve current generation and therefore maximum power.

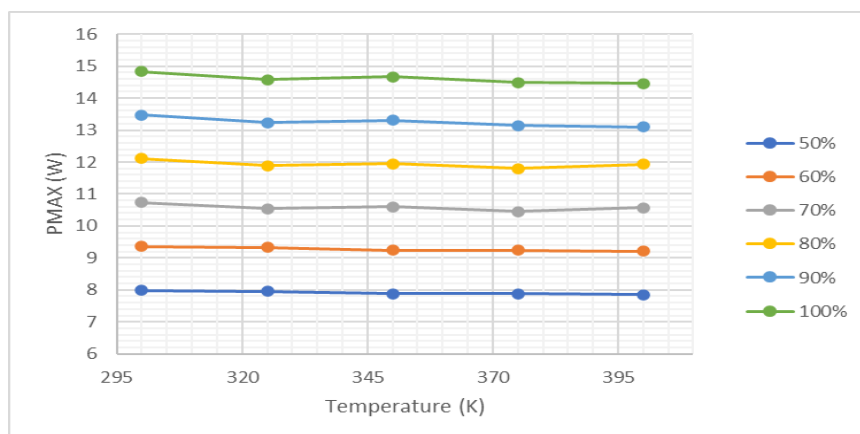


Figure 5: Maximum power density as a function of modeled optical attenuation at the investigated temperatures

Modeled Performance Recovery Using Lotus-Inspired Self-Cleaning

Figure 6 presents the modeled normalized power retention for a conventional surface and for idealized self-cleaning surfaces with 30%, 50%, 70% and 90% cleaning efficiencies. At 50% modeled optical attenuation, the conventional surface retained approximately 50% of the clean-surface power. The corresponding retained power was approximately 65%, 75%, 85% and 95% for cleaning efficiencies of 30%, 50%, 70% and 90%, respectively.

The improvement arises directly from the reduction in effective modeled optical attenuation in Equation (2). For example, at 50% modeled optical attenuation and 70% cleaning efficiency, the effective modeled optical attenuation becomes 15%. Under the linear transmission-loss assumption used in the model, this corresponds to approximately 85% power retention. Relative to the untreated 50%-attenuation case, the recovered fraction is $(85 - 50)/50 \times 100 = 70\%$.

The results indicate that the benefit of the bioinspired surface is primarily optical rather than electronic. The

model does not change carrier mobility, defect density, bandgap or interface properties after cleaning. Instead, it increases the fraction of incident light transmitted to the absorber. This distinction is important when interpreting the results: the predicted recovery represents the potential benefit of maintaining surface transmission, not a direct modification of semiconductor quality.

At 90% cleaning efficiency, the model predicts approximately 95% power retention even at 50% modeled optical attenuation. Such a result illustrates the potential value of self-cleaning concepts for photovoltaic systems exposed to persistent soiling. However, practical performance will depend on coating transparency, abrasion resistance, wetting behaviour, particle composition, rainfall characteristics and the spectral/angular dependence of dust scattering. Experimental studies and wavelength-resolved optical models are therefore required before these numerical retention values can be treated as device-level performance guarantees.

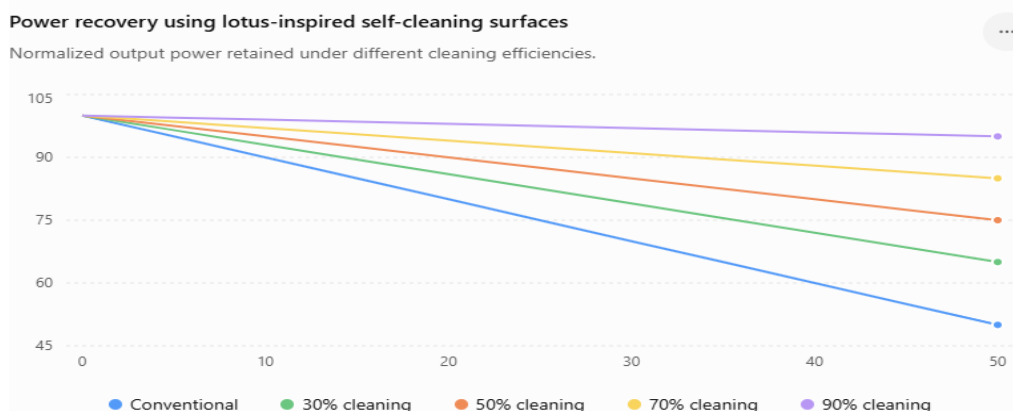


Figure 6: Normalized power retention versus modeled optical attenuation for a conventional surface and idealized lotus-inspired cleaning efficiencies of 30%, 50%, 70% and 90%

Limitations of the Study

The present dust model treats soiling as broadband neutral-density attenuation. It therefore does not resolve wavelength-dependent scattering or absorption, particle-size distributions, mineral composition, humidity effects, incidence angle, spatially non-uniform deposition or time-dependent accumulation. Likewise, the lotus-inspired model represents self-cleaning as a prescribed removal efficiency rather than explicitly simulating hierarchical surface morphology, contact-angle hysteresis, droplet motion or particle adhesion. These assumptions make the model useful for first-order device-level sensitivity analysis but limit direct comparison with a particular coating or outdoor installation. Future work should combine measured spectral transmittance, optical ray tracing and experimentally measured cleaning efficiencies with device simulation.

CONCLUSION

This study used SCAPS-1D to quantify the effects of temperature and dust-induced optical attenuation on a $\text{SnO}_2/\text{CsPbI}_2\text{Br}/\text{CuI}$ perovskite solar cell and to estimate the potential benefit of a lotus-inspired self-cleaning concept. Temperature primarily modified the electrical response: V_{oc} decreased while FF increased over 300–400 K, producing comparatively modest changes in PCE. Dust attenuation had a different signature. Increasing modeled optical attenuation from 0% to 50% (corresponding to reducing optical transmission from 100% to 50%) produced an approximately proportional reduction in J_{sc} and maximum power, while V_{oc} and FF changed comparatively little.

The idealized self-cleaning model predicted progressively greater power retention as cleaning efficiency increased. At 50% modeled optical attenuation, modeled cleaning efficiencies of 30%, 50%, 70% and 90% retained approximately 65%, 75%, 85% and 95% of the clean-surface power, respectively. These results support the use of bio inspired surface engineering as a strategy for mitigating optical soiling losses, while emphasizing that the calculated values are model-dependent. Experimental validation, spectral optical characterization and explicit surface-wetting/particle-adhesion modeling are recommended to establish the practical performance of lotus-inspired photovoltaic surfaces.

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