

## Thin-film CdTe/CdS/ZnO solar cells and the path to affordable clean energy: Simulation-based evidence for sustainable photovoltaic design

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### Article history:

Received: September 29, 2025

1st Revision: January 24, 2026

Accepted: March 16, 2026

### JEL classification:

Q20

Q42

O33

Q54

### DOI:

[10.14254/jems.2026.11-1.4](https://doi.org/10.14254/jems.2026.11-1.4)

**Abstract:** Global decarbonization commitments have intensified demand for low-cost, scalable solar technologies, yet the gap between laboratory-scale device physics and real-world deployment economics remains poorly addressed in simulation-oriented research. This study examines the photovoltaic performance of a CdTe/CdS/ZnO thin-film solar cell using one-dimensional numerical simulation in SCAPS-1D, focusing on two parameters with direct implications for manufacturing costs and field performance: absorber layer thickness (0.05–2  $\mu\text{m}$ ) and operating temperature (300–400 K). Under standard test conditions (AM1.5G, 1000 W/m<sup>2</sup>, 300 K), the baseline device achieves an open-circuit voltage of 0.9482 V, a short-circuit current density of 10.43 mA/cm<sup>2</sup>, a fill factor of 76.79%, and a power conversion efficiency of 7.60%. Increasing absorber thickness progressively raises both current density and open-circuit voltage through enhanced photon capture and reduced bulk recombination, while the fill factor declines owing to greater series resistance. Rising temperature degrades open-circuit voltage, fill factor, and overall efficiency - from 7.6% at 300 K to 5.7% at 400 K - primarily through an exponential increase in reverse saturation current, whereas short-circuit current density remains largely insensitive to thermal variation. At an absorber thickness of approximately 1.5–2  $\mu\text{m}$ , efficiency approaches 21%, a threshold relevant to the commercial viability of CdTe modules. These findings carry concrete implications for sustainable energy

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deployment: reducing CdTe absorber thickness without sacrificing efficiency directly lowers material consumption and cadmium usage, easing both environmental and supply-chain concerns. The results provide simulation-based guidance for designing cost-competitive thin-film modules capable of supporting the SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) objectives, particularly in climate-stressed regions where thermal degradation is a persistent operational challenge.

**Keywords:** CdTe thin-film photovoltaics, SCAPS-1D simulation, sustainable energy, levelized cost of energy, SDG 7

**Sustainable Development Goals (SDGs):** SDG 7: Affordable and Clean Energy; SDG 13: Climate Action

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## 1. Introduction

The acceleration of climate change and rising global energy demand have placed renewable energy deployment at the centre of both scientific inquiry and policy design. The International Energy Agency projects that solar photovoltaics will account for the single largest share of new electricity capacity additions through 2030, with thin-film technologies occupying a strategically important niche due to their lower material intensity and reduced manufacturing energy requirements relative to conventional crystalline silicon modules (IEA, 2024). Within this landscape, cadmium telluride (CdTe) thin-film solar cells represent a commercially mature yet technically underoptimized technology: First Solar's utility-scale deployments have demonstrated that CdTe modules can deliver electricity at a levelized cost of approximately \$0.04/kWh, substantially below the national average cost across all generation sources in the United States (NREL, 2025). This cost advantage, combined with a relatively short energy payback period, positions CdTe photovoltaics as a credible contributor to SDG 7 - Affordable and Clean Energy - and SDG 13 - Climate Action.

Despite this commercial maturity, the physics of CdTe thin-film devices at the absorber-layer level remains an active area of inquiry, particularly regarding the trade-off between material thickness and device performance under real-world thermal conditions. Experimental optimization of these devices is time-consuming and resource-intensive; numerical simulation tools, particularly SCAPS-1D, have therefore become standard instruments for probing device behavior before committing to fabrication (Vicente et al., 2017; Zyoud et al., 2021). CdTe has a direct bandgap of approximately 1.45–1.5 eV and can theoretically absorb more than 95% of incident photons with energies above this threshold within just 1  $\mu\text{m}$  of material (Scarpulla et al., 2023). However, planar devices typically require absorbers thicker than 2  $\mu\text{m}$  to achieve competitive efficiencies because of recombination losses near the back contact, a constraint with tangible cost and environmental implications: more CdTe means more cadmium, a regulated heavy metal whose lifecycle management introduces non-trivial sustainability challenges (Maalouf et al., 2023). Reducing absorber thickness - while preserving or improving efficiency - thus sits at the intersection of device physics, manufacturing economics, and environmental stewardship.

The CdTe/CdS/ZnO heterojunction architecture studied here incorporates ZnO as a transparent conducting front contact, a design choice motivated by ZnO's large interfacial area and strong light-trapping properties, which enhance photocurrent generation and improve spectral response without requiring rare or expensive materials (Kartopu et al., 2018; Peter Amalathas & Alkai, 2019). CdS functions as the n-type buffer layer, and the CdTe absorber carries the primary photogeneration burden. Previous simulation studies using SCAPS-1D on comparable architectures have reported efficiencies ranging from roughly 10% for ultrathin absorbers to over 20% when absorber geometry is optimized (Bhari et al., 2023; Mekky, 2025), yet most of this work stops short of translating device-level insights into economic or sustainability terms.

This study addresses that gap. Using SCAPS-1D, we systematically evaluate how CdTe absorber thickness and operating temperature govern the four principal photovoltaic parameters: open-circuit voltage ( $V_{oc}$ ), short-circuit current density ( $J_{sc}$ ), fill factor (FF), and power conversion efficiency ( $\eta$ ). Beyond the device physics, we interpret the results through the lens of sustainable energy economics - specifically, what the identified optimal thickness range implies for material

consumption, manufacturing cost, and thermal-resilience requirements in hot climatic zones where solar irradiance is highest but ambient temperatures may substantially erode device output. The remainder of the paper is organized as follows: Section 2 describes the simulation methodology and material parameters; Section 3 presents results for J-V characteristics, quantum efficiency, temperature effects, absorber thickness effects, and series resistance; Section 4 discusses the findings in the context of sustainable photovoltaic design and economic deployment; Section 5 concludes with implications for research and practice.

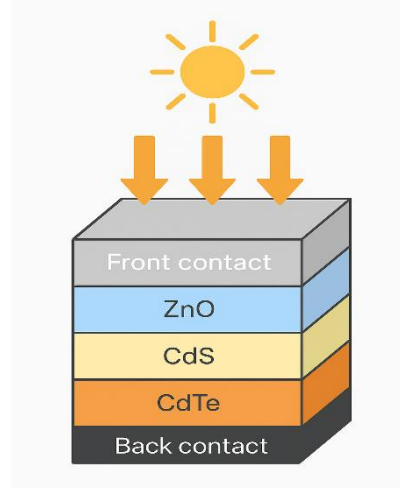
## 2. Simulation methodology

SCAPS-1D is a widely used numerical simulation tool for modeling, analyzing, and optimizing photovoltaic devices by precisely specifying their physical and electronic parameters. In this study, a CdTe/CdS/ZnO solar cell (Figure 1) is investigated to evaluate key photovoltaic parameters and assess the influence of operating conditions on device performance.

The study is organized in two analytical phases. The first examines the effect of operating temperature, varied from 300 to 400 K in increments of 25 K, on the cell's electrical output - a range chosen to reflect realistic deployment conditions from temperate climates to desert environments where CdTe installations are increasingly common (Buonomenna, 2023). The second phase evaluates the influence of CdTe absorber layer thickness, varied from 0.05 to 2  $\mu\text{m}$ , while holding the CdS and ZnO layer thicknesses constant, thereby isolating the absorber as the primary design variable with direct consequences for material cost and cadmium intensity.

The material parameters used in the simulations are summarized in Table 1. It should be noted that the simulations are performed without explicitly considering contact properties or interface defects, in order to highlight the intrinsic behavior of the active layers under the applied external conditions.

**Figure 1: Structural design of a ZnO/CdS/CdTe heterojunction solar cell**



**Table 1: Key physical parameters utilized in the SCAPS simulations**

Parameters	CdTe	CdS	ZnO
Thickness ( $\mu\text{m}$ )	0.05	0.5	0.8
Bandgap, $E_g$ (eV)	1.5	2.4	3.3
Electron Affinity, $X_e$ (eV)	3.9	4.1	4.4
Dielectric constant, $\epsilon_r$	9.4	10	9
$C_B$ ( $\text{cm}^{-3}$ )	$8 \cdot 10^{17}$	$2.2 \cdot 10^{18}$	$2.2 \cdot 10^{18}$
$V_B$ ( $\text{cm}^{-3}$ )	$1.8 \cdot 10^{19}$	$1.8 \cdot 10^{19}$	$1.8 \cdot 10^{19}$
Electron thermal velocity (cm/s)	$10^{17}$	$10^{17}$	$10^{17}$
Hole thermal velocity (cm/s)	$10^{17}$	$10^{17}$	$10^{17}$
Electron mobility ( $\text{cm}^2/\text{Vs}$ )	$3.2 \cdot 10^2$	$10^2$	10
Hole mobility ( $\text{cm}^2/\text{Vs}$ )	$4 \cdot 10^1$	$2.3 \cdot 10$	2.5
$N_D$ ( $\text{cm}^{-3}$ )	0	$8 \cdot 10^{17}$	$1 \cdot 10^{18}$
$N_A$ ( $\text{cm}^{-3}$ )	$2 \cdot 10^{14}$	0	0

It is important to acknowledge a methodological simplification in the present simulations: interface defect states between the CdTe/CdS and CdS/ZnO junctions, as well as back-contact properties, are not explicitly modeled. This choice isolates the intrinsic behavior of the active layers under the applied conditions and follows a convention adopted in comparable simulation studies (Bhari et al., 2023; Parashar et al., 2020). However, it implies that the simulated efficiencies represent

upper-bound estimates; real fabricated devices would be expected to exhibit somewhat lower performance due to interface recombination and contact resistance. Future work incorporating these effects would improve the model's predictive accuracy and utility for manufacturing process optimization.

### 3. Results and discussion

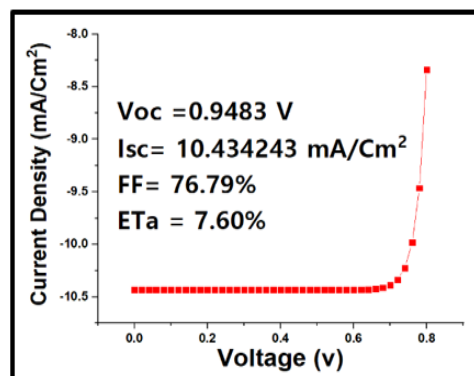
#### 3.1. J-V and QE

Figure 2 shows the current-voltage (I-V) curve of the CdTe/CdS/ZnO solar cell, simulated under standard test conditions (AM1.5G illumination, 1000 W/m<sup>2</sup>, and 300 K), demonstrating characteristic photovoltaic behavior. The cell achieves a remarkable open-circuit voltage (V<sub>oc</sub>) of 0.9482 V and a high short-circuit current density (J<sub>sc</sub>) of 10.4342 mA/cm<sup>2</sup>, indicating efficient photon-to-charge conversion (Jin et al., 2012). The fill factor (FF) of 76.79% highlights the excellent quality of the diode and the relatively low series resistance, two essential factors for optimizing overall device performance (Williams et al., 2014).

The power conversion efficiency ( $\eta$ ) of 7.60% achieved places the cell within the typical average performance range of thin-film CdTe-based solar cells. This efficiency demonstrates an optimal combination of material properties and device architecture. Furthermore, the shape and behavior of the I-V curve, as well as the extracted parameters, suggest efficient separation and collection of charge carriers within the device, confirming the effectiveness of the CdTe/CdS/ZnO heterojunction in minimizing recombination losses and improving the device's overall functionality.

Before examining individual parameter effects, it is worth situating the baseline result within the broader technology landscape. The simulated baseline efficiency of 7.60% falls in the lower range of what SCAPS-1D studies on similar CdTe architectures typically report, and well below the 22.1% laboratory record and 18.6% commercial module efficiency documented in the literature (Ali et al., 2017; Scarpulla et al., 2023). This gap is attributable in large part to the intentional simplifications of the present model - most notably the exclusion of interface defects and optimized back-contact engineering - and to the relatively thin baseline absorber (0.05  $\mu$ m). The value of the present analysis lies not in replicating record performance, but in mapping how two practically controllable variables - thickness and temperature - drive device behavior across a parameter space directly relevant to deployment decisions.

**Figure 2: Current-voltage response of CdTe/CdS/ZnO solar cell under standard operating conditions**

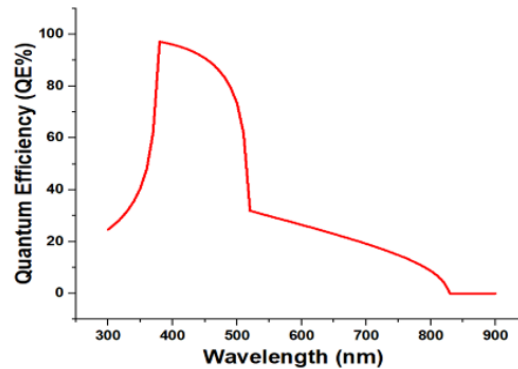


Quantum efficiency (QE%) provides essential information about a solar cell's spectral response and carrier collection efficiency. It establishes a direct link between photon absorption and charge carrier generation and collection, thereby identifying the wavelength ranges where the device performs well or suffers losses. In this study, QE analysis complements standard current-voltage characterization, allowing the evaluation of the effects of temperature, CdTe layer thickness, and series resistance on the intrinsic photo-response of the CdTe/CdS/ZnO solar cell. QE thus serves as a key diagnostic tool for optimizing layer thicknesses and material properties to maximize overall device performance (Farah Khaleda et al., 2021).

Figure 3 shows the external quantum efficiency (QE%) as a function of wavelength, from 300 to 900 nm. QE rises sharply from 300 nm, reaching a peak near 100% around 400 nm, indicating highly efficient photon absorption and carrier generation in the near-ultraviolet region. Between 400 and 500 nm, the curve exhibits a broad plateau, reflecting strong absorption in the visible range and efficient carrier collection, characteristic of the CdTe/CdS heterojunction. Beyond 500 nm, the QE

gradually decreases, which is consistent with the CdS bandgap ( $\sim 2.4$  eV), as lower-energy photons are absorbed less effectively. In the near-infrared region, the QE approaches zero around 850 nm, corresponding to photons with energies below the CdTe absorber bandgap. Minor contributions below the band gap may come from defect states or from impurities that limit absorption. Overall, the QE curve demonstrates that the solar cell is primarily active in the UV-visible range, with negligible response in the infrared, reflecting both the intrinsic optical properties of the materials and the influence of defects on carrier generation (Meng et al., 2022).

**Figure 3: Quantum efficiency (%) as a function of wavelength for CdTe/CdS/ZnO solar cell**



From a sustainability perspective, the quantum efficiency profile - peaking near 100% in the near-UV and declining gradually through the visible range - suggests that the device is well-suited to high-irradiance, low-latitude deployment environments. Regions in North Africa, the Middle East, and sub-Saharan Africa, where solar resources are most abundant, are also regions where energy poverty is most acute; efficient photon capture in the UV-visible range is therefore not merely a device physics metric but a precondition for equitable clean energy access aligned with SDG 7 (IEA, 2024).

### 3.2. Effect of operating temperature

Figure 4 presents the variation in the photovoltaic parameters of the CdTe solar cell as a function of operating temperature, from 300 to 400 K. The results show that the open-circuit voltage ( $V_{oc}$ ), fill factor (FF), and power conversion efficiency (PCE) decrease significantly with increasing temperature, while the short-circuit current density ( $J_{sc}$ ) remains nearly constant, showing only slight variation. The reduction in  $V_{oc}$  is primarily attributed to the exponential increase in reverse saturation current ( $I_0$ ) with temperature, according to reference (Bhari et al., 2023):

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{ph}}{I_0} + 1\right)$$

$V_{oc}$  is the open-circuit voltage, which represents the maximum voltage delivered by the solar cell when no external current is drawn (open-circuit condition).

$k$  is the Boltzmann constant ( $1.38 \times 10^{-23}$  J/K), which links thermal energy to temperature.

$T$  is the absolute temperature of the solar cell, expressed in Kelvin (K).

$q$  is the elementary charge of an electron  $1.602 \times 10^{-19}$  C

$\ln$  refers to the natural logarithm.

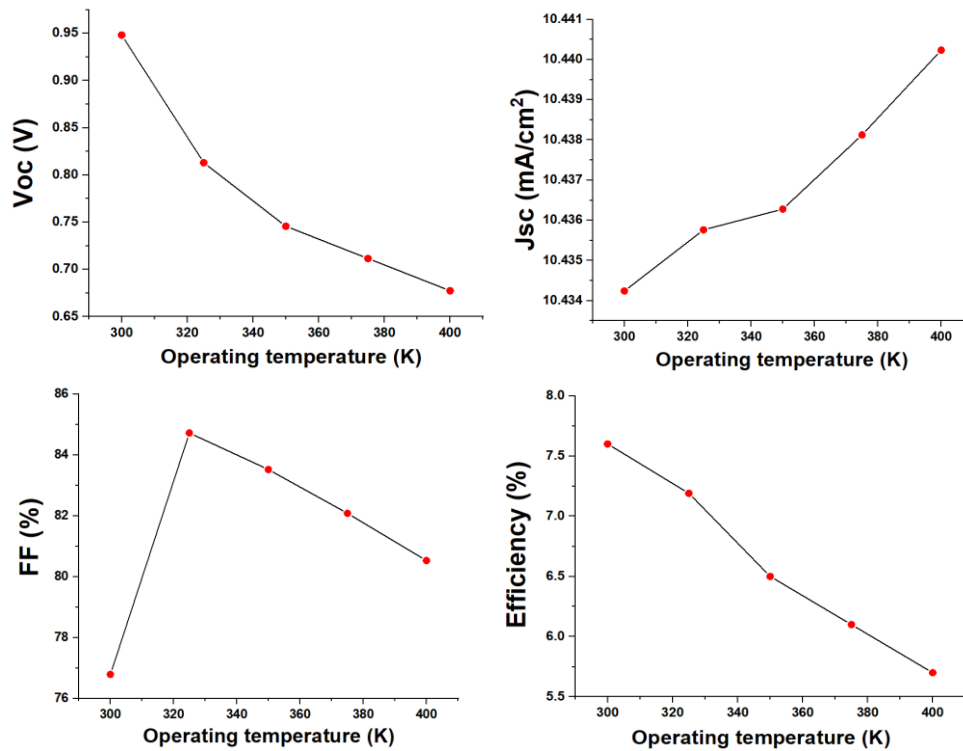
$I_{ph}$  is the photogenerated current, which is directly proportional to the incident photon flux absorbed by the solar cell.

$I_0$  is the reverse saturation current, which originates from carrier recombination within the junction in the absence of light. It is highly temperature-dependent and increases exponentially with temperature.

Furthermore, the narrowing of the band gap at high temperatures enhances carrier recombination, further contributing to the decrease in  $V_{oc}$ . The low-temperature dependence of  $J_{sc}$  can be explained by the fact that photon absorption in CdTe is not strongly affected by thermal effects, although recombination losses at higher temperatures limit any noticeable increase in photocurrent. The decrease in FF is mainly related to resistive effects: the series resistance increases as the carrier diffusion length decreases, while the shunt resistance decreases due to leakage currents and recombination, both of which degrade the shape of the J-V curve. Consequently, the overall efficiency decreases from 7.6% at 300 K to 5.7% at 400 K, as the combined losses in open-circuit voltage ( $V_{oc}$ ) and fill factor (FF) become predominant over the short-circuit current density ( $J_{sc}$ ), which remains

virtually stable. These results highlight the high sensitivity of CdTe solar cell performance to operating temperature, underscoring the importance of optimizing material properties and device architecture to limit thermal recombination and resistive losses.

**Figure 4: Influence of temperature on Voc, Jsc, FF, and efficiency**



The practical implication of this temperature sensitivity is significant for deployment economics. In regions such as the Sahel or the Arabian Peninsula - precisely those areas where solar irradiance is most intense - ambient module temperatures routinely reach 340–360 K under full-sun conditions, compressing expected efficiency toward the lower end of the simulated range. This is not merely a performance concern; a reduction in efficiency from 7.6% to 5.7% over a 100 K temperature rise translates directly into a higher levelized cost of energy (LCOE), since fewer kilowatt-hours are generated per unit of installed capacity. Thermal management strategies - including module ventilation design, reflective mounting structures, and the development of CdTe alloys with higher bandgap stability - therefore represent important areas for future applied research (Scarpulla et al., 2023).

### 3.3. Influence of CdTe absorber layer thickness

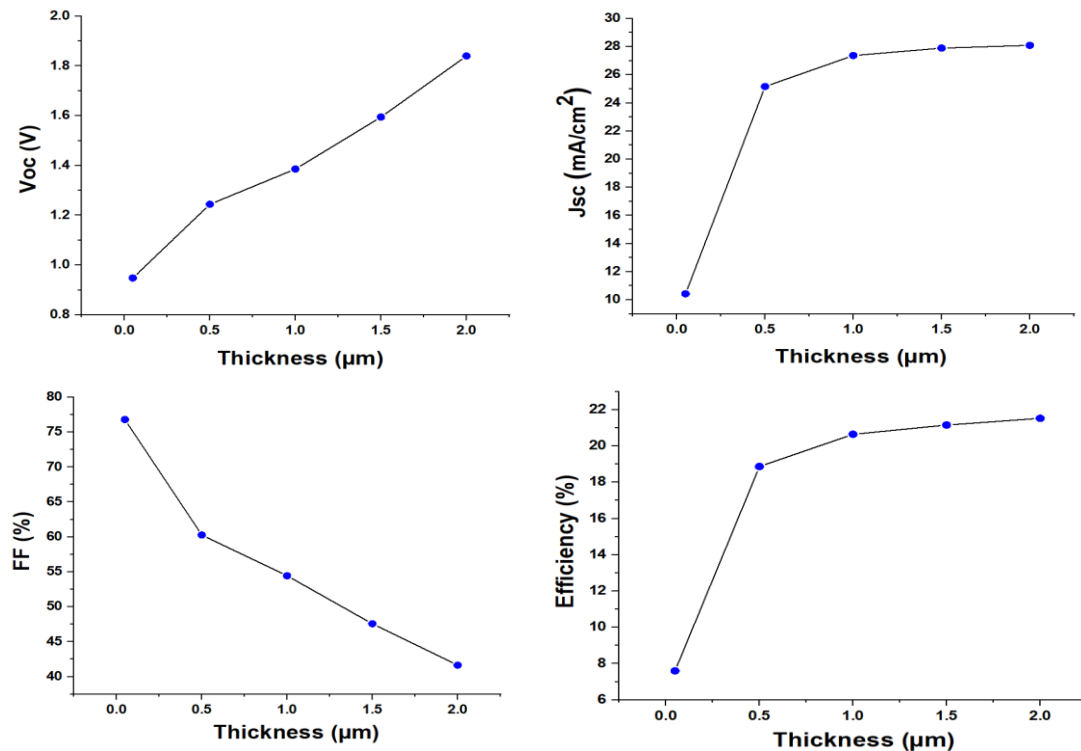
Figure 5 illustrates the influence of the CdTe absorber layer thickness on the main key photovoltaic parameters: open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and power conversion efficiency ( $\eta$ ). It can be observed that increasing the CdTe thickness from 0.05  $\mu\text{m}$  to 2  $\mu\text{m}$  results in a significant increase in Jsc (from 10.43 to 28.09 mA/cm<sup>2</sup>). This is explained physically by the fact that a thicker absorber layer captures more photons, thereby generating a larger number of electron-hole pairs. Voc also increases (from 0.95 V to 1.84 V), but more moderately. This increase results from reduced bulk recombination, as a thicker layer allows for more efficient separation of charge carriers before they recombine (Mekky, 2025).

However, the fill factor (FF) decreases with increasing thickness (from 76.79% to 41.65%), which may seem counterintuitive. This trend reflects an increase in resistive losses and recombination as the layer thickens, thereby reducing charge-collection efficiency (Simya et al., 2015).

Finally, the overall efficiency ( $\eta$ ) rises quickly with initial thickness, reaching around 21 % for 1.5 to 2  $\mu\text{m}$ . Beyond a certain thickness, further absorption gains no longer significantly improve efficiency because transport losses and recombination begin to offset the optical advantages.

In summary, these results show that the optimal CdTe thickness lies in an intermediate range, where maximum light absorption and efficient carrier extraction allow the highest possible efficiency.

**Figure 5: Impact of absorber layer thickness variations on the Voc, Jsc, FF, and efficiency**



The identification of an optimal thickness in the 1.5–2  $\mu\text{m}$  range has a direct economic dimension. Cadmium telluride is a scarce material - global tellurium production is approximately 500 tonnes per year, and competing demands from thermoelectric and other applications create supply-chain vulnerability at the terawatt scale (Buonomenna, 2023). Reducing the absorber thickness from the conventional  $>2 \mu\text{m}$  benchmark to the 1.5  $\mu\text{m}$  range identified here, while maintaining an efficiency near 21%, could meaningfully reduce per-watt material consumption and contribute to the long-term resource sustainability of CdTe photovoltaics. This is consistent with the broader industry trajectory toward ultrathin absorber designs enabled by advanced light-trapping architectures (Kartopu et al., 2018).

### 3.4. Effect of series resistance ( $R_s$ )

Series resistance ( $R_s$ ) is among the most practically consequential non-idealities in thin-film solar cells, arising from contact resistance, bulk material resistivity, and lateral transport through the transparent conducting layer. As  $R_s$  increases from its baseline value, the simulation results show that Voc remains essentially stable - consistent with its dependence on junction quality rather than resistive losses - while Jsc and FF both decline progressively. This behavior reflects the physical mechanism by which series resistance distorts the J-V curve: at high current densities, the resistive voltage drop reduces the terminal voltage available from the cell, shifting the operating point away from maximum power. The resulting decline in FF, even when open-circuit voltage is preserved, directly reduces power conversion efficiency and consequently raises the LCOE of any installation based on such devices. These results reinforce the practical importance of minimizing contact and sheet resistance during module fabrication - a manufacturing process variable that simulation alone cannot fully capture but which techno-economic optimization models must account for (Peña et al., 2011; Oman et al., 1999).

## 4. Sustainability and deployment implications

The simulation results presented in Section 3 carry implications that extend beyond device physics into the domains of sustainable energy economics and climate policy. Three dimensions deserve particular attention.

The first concerns material efficiency. At the optimal absorber thickness of approximately 1.5–2  $\mu\text{m}$  identified in this study, the CdTe layer delivers near-peak efficiency while consuming less than a full standard commercial absorber specification. Given that tellurium - the rarer of the two constituent elements - is produced primarily as a byproduct of copper refining and is subject to supply volatility, any reduction in per-watt CdTe usage directly improves the technology's resource sustainability at scale (Buonomenna, 2023; Maalouf et al., 2023). Life cycle assessments of commercial CdTe modules have consistently demonstrated that CdTe photovoltaics exhibit shorter energy payback times and lower greenhouse gas emission intensities than crystalline silicon counterparts. This sustainability advantage grows further as absorber thickness decreases and manufacturing energy per watt declines (Maalouf et al., 2023).

The second dimension is climatic suitability. The temperature analysis in Section 3.2 shows that efficiency declines from 7.6% at 300 K to 5.7% at 400 K - a 25% relative reduction over a 100 K range. While this range is broader than typical real-world diurnal temperature swings, it is directly relevant to comparing performance across deployment latitudes. Desert regions in North Africa, the Arabian Peninsula, and sub-Saharan Africa represent the world's highest-irradiance zones and, simultaneously, regions with the greatest energy access deficits. The tension between high solar resource availability and elevated operating temperatures is not a trivial engineering footnote; it is a deployment constraint that affects the financial viability of projects and, ultimately, the speed at which solar energy can help eliminate energy poverty in line with SDG 7. Developing CdTe device architectures that maintain high efficiency under elevated thermal conditions - through bandgap engineering, improved back-contact passivation, or module-level thermal management - is therefore a research priority with direct sustainability relevance (Scarpulla et al., 2023).

The third dimension is economic accessibility. The levelized cost of energy from utility-scale CdTe installations is already among the lowest of any electricity generation technology - approximately \$0.04/kWh in recent estimates - and further efficiency improvements enabled by optimized absorber geometries can only strengthen this cost position (NREL, 2025). For policymakers in emerging economies designing feed-in tariff structures, renewable portfolio standards, or off-grid electrification programs, simulation-based evidence of the absorber thickness-efficiency trade-off provides actionable guidance: investing in deposition process control to achieve uniform 1.5  $\mu\text{m}$  CdTe absorber layers, rather than defaulting to thicker absorbers as a safety margin, offers a quantifiable path to reducing module cost per watt without sacrificing performance. This kind of design-to-economics linkage - connecting materials simulation to deployment cost modeling - represents an underexplored frontier in the thin-film photovoltaics literature.

## 5. Conclusion

This study employed SCAPS-1D numerical simulations to map the photovoltaic performance of a CdTe/CdS/ZnO thin-film solar cell across two experimentally controllable variables: absorber layer thickness (0.05–2  $\mu\text{m}$ ) and operating temperature (300–400 K). The analysis confirms that increasing the CdTe thickness from ultrathin to approximately 1.5–2  $\mu\text{m}$  substantially increases  $J_{sc}$  and  $V_{oc}$  through enhanced photon capture and reduced bulk recombination, while the fill factor declines owing to higher series resistance and longer carrier transport paths. An optimal thickness window of 1.5–2  $\mu\text{m}$ , yielding efficiency near 21%, emerges as the design target that best balances light absorption against carrier collection efficiency. Rising operating temperature degrades  $V_{oc}$ , FF, and overall power conversion efficiency - the latter falling from 7.6% at 300 K to 5.7% at 400 K - primarily through an exponential increase in reverse saturation current and modest bandgap narrowing, while  $J_{sc}$  remains nearly temperature-invariant (Bhari et al., 2023).

From a scientific standpoint, these findings extend the SCAPS-1D simulation literature on CdTe/CdS/ZnO devices by explicitly framing absorber thickness and thermal sensitivity as co-determinants of deployment viability, rather than treating them as isolated physical parameters. The results are consistent with, and complementary to, recent experimental and computational work on ultrathin CdTe architectures (Mekky, 2025; Scarpulla et al., 2023; Kartopu et al., 2018).

From a practical and sustainability perspective, the identification of an optimal thickness range of 1.5–2  $\mu\text{m}$  carries direct implications for manufacturing process design and resource efficiency. Reducing CdTe absorber thickness toward this range lowers per-watt cadmium consumption, shortens energy payback time, and reduces supply-chain exposure to tellurium scarcity - all of which improve the environmental and economic sustainability profile of CdTe photovoltaics at the gigawatt scale (Buonomenna, 2023; Maalouf et al., 2023). The temperature sensitivity findings, meanwhile, underscore the importance of thermal management in deployment contexts where ambient temperatures are elevated, particularly in the high-irradiance regions of Africa and the Middle East, where CdTe technology could play a transformative role in closing the energy access gap consistent with SDG 7 and SDG 13 (IEA, 2024).

Several limitations of the present study should guide future work. The simulations exclude interface defect states and back-contact resistance, which means the reported efficiencies represent optimistic upper bounds for ideal-case devices. Incorporating interface engineering effects - back-surface field layers, passivation treatments, and realistic contact work functions - into the simulation would substantially improve the model's predictive power for real fabricated cells. Beyond device physics, integrating SCAPS-1D output with techno-economic models capable of calculating LCOE as a function of absorber thickness and operating climate would bridge the gap between simulation-derived design optima and deployment-ready engineering decisions. Such an integrated framework represents a promising direction for future research at the intersection of materials science, energy economics, and sustainability.

## Author contributions

Conceptualization: *Driss Akhlidej*; methodology: *Abdelhalim Elbasset, Najiba El Idrissi El Amrani*; data analysis: *Driss Akhlidej, Abdelhalim Elbasset, Najiba El Idrissi El Amrani*; writing-original draft preparation: *Driss Akhlidej, Abdelhalim Elbasset*; writing, review, and editing: *Najiba El Idrissi El Amrani, Farid Abdi, Taj-dine Lamcharfi, Yuriy Bilan*; Beata Szetela; visualization: *Yuriy Bilan, Beata Szetela*. All authors have read and agreed to the published version of the manuscript.

## Funding

The research leading to these results has received funding from the project titled "Cluster for innovative energy" in the frame of the program "HORIZON-MSCA-2022-SE-01" under the Grant agreement number 101129820.

## Conflict of interest

The authors declare no conflicts of interest. Both authors have no financial or personal relationships with individuals or organizations that could inappropriately influence or bias the content of this manuscript.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Grammarly (Premium version) to enhance the clarity, grammar, and readability of the English language text. Grammarly was employed solely for language editing purposes, including correction of grammatical errors, improvement of sentence structure, and refinement of word choice.

## Citation information

Akhlidej, D., Elbasset, A., El Amrani El Idrissi, N., Bilan, Y., Szetela, B., Abdi, F., & Lamcharfi, T.-D. (2026). Thin-film CdTe/CdS/ZnO solar cells and the path to affordable clean energy: Simulation-based evidence for sustainable photovoltaic design. *Economics, Management and Sustainability*, 11(1), 84-94. doi:10.14254/jems.2026.11-1.4.

## References

- Ahmed, S., Aktar, A., Rahman, Md. F., Hossain, J., & Ismail, A. B. Md. (2020). A numerical simulation of high efficiency CdS/CdTe based solar cell using NiO HTL and ZnO TCO. *Optik*, 223, 165625. <https://doi.org/10.1016/j.ijleo.2020.165625>
- Ali, A. M., Rahman, K. S., Ali, L. M., Akhtaruzzaman, M., Sopian, K., Radiman, S., & Amin, N. (2017). A computational study on the energy bandgap engineering in performance enhancement of CdTe thin film solar cells. *Results in Physics*, 7, 1066-1072. <https://doi.org/10.1016/j.rinp.2017.02.032>
- Bhari, B. Z., Rahman, K. S., Chelvanathan, P., & Ibrahim, M. A. (2023). Numerical Simulation of Ultrathin CdTe Solar Cell by SCAPS-1D. *IOP Conference Series: Materials Science and Engineering*, 1278(1), 012002. <https://doi.org/10.1088/1757-899X/1278/1/012002>

- Buonomenna, M. G. (2023). Inorganic Thin-Film Solar Cells: Challenges at the Terawatt-Scale. *Symmetry*, 15(9), 1718. <https://doi.org/10.3390/sym15091718>
- Farah Khaleida, M. Z., Vengadaesvaran, B., & Rahim, N. A. (2021). Spectral response and quantum efficiency evaluation of solar cells: A review. In *Energy Materials* (pp. 525–566). Elsevier. <https://doi.org/10.1016/B978-0-12-823710-6.00014-5>
- Heriche, H., Rouabah, Z., & Bouarissa, N. (2017). New ultra thin CIGS structure solar cells using SCAPS simulation program. *International Journal of Hydrogen Energy*, 42(15), 9524–9532. <https://doi.org/10.1016/j.ijhydene.2017.02.099>
- IEA. (2024). World Energy Outlook 2024. International Energy Agency. <https://www.iea.org/reports/world-energy-outlook-2024>
- Jin, M.-J., Chen, X.-Y., Gao, Z.-M., Ling, T., & Du, X.-W. (2012). Improve photo-electron conversion efficiency of ZnO/CdS coaxial nanorods by p-type CdTe coating. *Nanotechnology*, 23(48), 485401. <https://doi.org/10.1088/0957-4484/23/48/485401>
- Kartopu, G., Turkay, D., Ozcan, C., Hadibrata, W., Aurang, P., Yerci, S., Unalan, H. E., Barrioz, V., Qu, Y., Bowen, L., Gürlek, A. K., Maiello, P., Turan, R., & Irvine, S. J. C. (2018). Photovoltaic performance of CdS/CdTe junctions on ZnO nanorod arrays. *Solar Energy Materials and Solar Cells*, 176, 100–108. <https://doi.org/10.1016/j.solmat.2017.11.036>
- Maalouf, A., Okoroafor, T., Jehl, Z., Babu, V., & Resalati, S. (2023). A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems. *Renewable and Sustainable Energy Reviews*, 186, 113652. <https://doi.org/10.1016/j.rser.2023.113652>
- Mekky, A. H. (2025). A Comprehensive Simulation Study of CdTe Energy Gap Effects on CdTe/CdS Solar Cell Characteristics: SCAPS-1D. *Periodica Polytechnica Chemical Engineering*. <https://doi.org/10.3311/PPch.38728>
- Meng, X., Tang, T., Zhang, R., Liu, K., Li, W., Yang, L., Song, Y., Ma, X., Cheng, Z., & Wu, J. (2022). Optimization of germanium-based perovskite solar cells by SCAPS simulation. *Optical Materials*, 128, 112427. <https://doi.org/10.1016/j.optmat.2022.112427>
- NREL. (2025). Levelized cost of energy calculator. National Renewable Energy Laboratory. <https://www.nrel.gov/analysis/tech-lcoe.html>
- Oman, D. M., Dugan, K. M., Killian, J. L., Ceekala, V., Ferekides, C. S., & Morel, D. L. (1999). Device performance characterization and junction mechanisms in CdTe/CdS solar cells. *Solar Energy Materials and Solar Cells*, 58(4), 361–373. [https://doi.org/10.1016/S0927-0248\(99\)00008-2](https://doi.org/10.1016/S0927-0248(99)00008-2)
- Parashar, D., Krishna, V. S. G., Moger, S. N., Keshav, R., & Mahesha, M. G. (2020). Thickness Optimization of ZnO/CdS/CdTe Solar Cell by Numerical Simulation. *Transactions on Electrical and Electronic Materials*, 21(6), 587–593. <https://doi.org/10.1007/s42341-020-00209-9>
- Paudel, N. R., Wieland, K. A., & Compaan, A. D. (2012). Ultrathin CdS/CdTe solar cells by sputtering. *Solar Energy Materials and Solar Cells*, 105, 109–112. <https://doi.org/10.1016/j.solmat.2012.05.035>
- Peña, J. L., Arés, O., Rejón, V., Rios-Flores, A., Camacho, J. M., Romeo, N., & Bosio, A. (2011). A detailed study of the series resistance effect on CdS/CdTe solar cells with Cu/Mo back contact. *Thin Solid Films*, 520(2), 680–683. <https://doi.org/10.1016/j.tsf.2011.04.193>
- Peter Amalathas, A., & Alkaisi, M. (2019). Nanostructures for Light Trapping in Thin Film Solar Cells. *Micromachines*, 10(9), 619. <https://doi.org/10.3390/mi10090619>
- Scarpulla, M. A., McCandless, B., Phillips, A. B., Yan, Y., Heben, M. J., Wolden, C., Xiong, G., Metzger, W. K., Mao, D., Krasikov, D., Sankin, I., Grover, S., Munshi, A., Sampath, W., Sites, J. R., Bothwell, A., Albin, D., Reese, M. O., Romeo, A., ... Hayes, S. M. (2023). CdTe-based thin film photovoltaics: Recent advances, current challenges and future prospects. *Solar Energy Materials and Solar Cells*, 255, 112289. <https://doi.org/10.1016/j.solmat.2023.112289>
- Simya, O. K., Mahaboobbatcha, A., & Balachander, K. (2015). A comparative study on the performance of Kesterite based thin film solar cells using SCAPS simulation program. *Superlattices and Microstructures*, 82, 248–261. <https://doi.org/10.1016/j.spmi.2015.02.020>
- Sivaraj, S., Rathanasamy, R., Kaliyannan, G. V., Panchal, H., Jawad Alrubaie, A., Musa Jaber, M., Said, Z., & Memon, S. (2022). A Comprehensive Review on Current Performance, Challenges and Progress in Thin-Film Solar Cells. *Energies*, 15(22), 8688. <https://doi.org/10.3390/en15228688>

- Vicente, A. T., Wojcik, P. J., Mendes, M. J., Águas, H., Fortunato, E., & Martins, R. (2017). A statistics modeling approach for the optimization of thin film photovoltaic devices. *Solar Energy*, 144, 232–243. <https://doi.org/10.1016/j.solener.2017.01.029>
- Williams, B. L., Major, J. D., Bowen, L., Phillips, L., Zoppi, G., Forbes, I., & Durose, K. (2014). Challenges and prospects for developing CdS/CdTe substrate solar cells on Mo foils. *Solar Energy Materials and Solar Cells*, 124, 31–38. <https://doi.org/10.1016/j.solmat.2014.01.017>
- Zyoud, S. H., Zyoud, A. H., Ahmed, N. M., & Abdelkader, A. F. I. (2021). Numerical Modelling Analysis for Carrier Concentration Level Optimization of CdTe Heterojunction Thin Film–Based Solar Cell with Different Non-Toxic Metal Chalcogenide Buffer Layers Replacements: Using SCAPS–1D Software. *Crystals*, 11(12), 1454. <https://doi.org/10.3390/cryst11121454>



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