Jurnal Teknosains: Jurnal Ilmiah Sains dan Teknologi
ISSN 2088-5415 (Print) | ISSN 2443-1311 (Online)
Vol. 16, No. 1, 35-47, December 2025
https://doi.org/10.22146/teknosains.109079
Submitted: 2025-07-10; Revised: 2025-10-02; Accepted:2025-10-03

JURNAL TEKNOSAINS

Numerical simulation of layer thickness optimization in perovskite solar cells for enhanced power conversion efficiency

Indonesian title: Simulasi numerik optimasi ketebalan lapisan pada sel surya perovskit untuk meningkatkan efisiensi konversi daya

***Soni Prayogi*[1,2*]**
[1]Department of Electrical Engineering, Pertamina University
[2]Advanced Materials Research Group, Institut Teknologi Sepuluh Nopember

ABSTRAK

Sel surya perovskit (PSC) telah mendapatkan perhatian signifikan karena efisiensi konversi daya (PCE) yang luar biasa dan potensi produksi yang terjangkau dan berskala. Meskipun ada kemajuan ini, peningkatan efisiensi lebih lanjut memerlukan optimasi sistematis arsitektur perangkat, khususnya ketebalan lapisan fungsional. Studi ini menyajikan simulasi numerik menggunakan platform simulasi OGMANANO untuk menyelidiki pengaruh variasi ketebalan lapisan khususnya pada lapisan penyerap perovskit, lapisan transpor elektron (ETL), dan lapisan transpor lubang (HTL) terhadap kinerja PSC planar. Simulasi ini memodelkan perangkat berstruktur n-i-p tipikal di bawah pencahayaan AM1.5G standar, mengevaluasi parameter fotovoltaik utama seperti kerapatan arus hubung singkat (Jsc), tegangan hubung terbuka (Voc), faktor pengisian (FF), dan PCE keseluruhan. Hasil menunjukkan bahwa ketebalan penyerap optimal terletak pada kisaran 500–600 nm, dengan efisiensi puncak 22,7% dicapai pada 550 nm. Lebih lanjut, ETL dan HTL menunjukkan kinerja optimal masing-masing pada 50 nm dan 60 nm, meminimalkan kehilangan rekombinasi dan meningkatkan transpor muatan. Studi ini menyimpulkan bahwa kontrol ketebalan lapisan yang presisi sangat penting untuk memaksimalkan efisiensi PSC. Penggunaan OGMANANO terbukti efektif dalam mensimulasikan struktur perovskit multilapis, menyediakan alat yang andal untuk optimasi prafabrikasi dalam desain sel surya canggih.

Keywords: *Ketebalan Lapisan; Simulasi Numerik; OGMANANO; Sel Surya Perovskit; Efisiensi Konversi Daya.*

ABSTRACT

Perovskite solar cells (PSCs) have gained significant attention due to their remarkable power conversion efficiency (PCE) and potential for low-cost, scalable production. Despite this progress, further efficiency enhancement requires systematic optimization of device architecture, particularly the thickness of functional layers. This study presents a numerical simulation using the OGMANANO simulation platform to investigate the influence of layer thickness variation, specifically in the perovskite absorber layer, electron transport layer (ETL), and hole transport layer (HTL), on the performance of planar PSCs. The simulation models a typical n-i-p structured device under standard AM1.5G illumination, evaluating key photovoltaic parameters such as short-circuit current density (Jsc), open-circuit voltage (Voc), fill factor (FF), and overall PCE. Results indicate that the optimal absorber thickness lies in the 500–600 nm range, with a peak efficiency of 22.7% achieved at 550 nm. Furthermore, ETL

*Corresponding author: soni.prayogi@universitaspertamina.ac.id

and HTL show optimal performance at 50 and 60 nm, respectively, minimizing recombination losses and enhancing charge transport. The study concludes that precise layer thickness control is critical for maximizing PSC efficiency. The use of OGMANANO proved effective in simulating multilayer perovskite structures, providing a reliable tool for pre-fabrication optimization in advanced solar cell design.

Keywords: *Layer Thickness; Numerical Simulation; OGMANANO; Perovskite Solar Cells,;Power Conversion Efficiency.*

INTRODUCTION

In the past decade, *perovskite solar cells* (PSCs) have emerged as one of the most transformative innovations in photovoltaic technology. PSCs have rapidly evolved since their initial development in 2009, with *power conversion efficiencies* (PCEs) increasing from below 4% to over 25%, rivaling those of well-established crystalline silicon solar cells (Wu & Chou, 2014). This rapid progress is largely attributed to the unique optoelectronic properties of perovskite materials, including a tunable bandgap, high absorption coefficient, long carrier diffusion lengths, and low exciton binding energies. These materials' inherent versatility allows various compositional, structural, and interface engineering approaches to optimize device performance (Darminto et al., 2023).

However, despite the remarkable achievements, commercial viability remains a challenge due to issues related to long-term stability, large-area scalability, and the need for further efficiency improvements under real-world conditions. Among the many factors affecting PSC performance, device architecture and particularly the thickness of each functional layer, such as the perovskite absorber, *electron transport layer* (ETL), and *hole transport layer* (HTL), play a pivotal role (Akiyama et al., 2015). These layers govern light absorption, carrier transport, recombination dynamics, and ultimately, the efficiency and reliability of the solar cell.

An overly thick absorber layer may increase recombination losses, while a thinner layer may result in insufficient photon absorption (Phung et al., 2023). Likewise, variations in the ETL and HTL thicknesses can affect series resistance, energy level alignment, and interface quality (Azmer et al., 2017). As such, finding the optimal thickness for each layer is crucial for achieving the best trade-off between light-harvesting and electrical performance (Chilipi et al., 2020).

Although experimental approaches have yielded important insights into PSC optimization, they often involve complex fabrication procedures, high material consumption, and significant time and cost investments (Chilipi et al., 2020). In contrast, numerical simulations offer a fast, cost-effective, and reliable method to investigate the effects of various device parameters, such as material properties, geometrical configurations, and boundary conditions, on photovoltaic performance (Tseng et al., 2020). Through simulation, researchers can perform virtual experiments, predict behavior under different conditions, and systematically optimize device structures without physical prototyping. This approach is especially beneficial in the early design and prototyping stages of photovoltaic research and development (S. Liu et al., 2021).

In this context, numerical modeling using simulation platforms such as SCAPS-1D, COMSOL Multiphysics, and OGMANANO has gained prominence (Islam et al., 2025). These tools enable detailed analysis of charge carrier dynamics, electric field distribution, recombination mechanisms, and optical absorption within multilayer devices. Unlike SCAPS-1D, which is limited to one-dimensional structures, and COMSOL, which often requires extensive customization for nanostructured layers, OGMANANO provides specialized features for photovoltaic device modeling. These include more accurate treatment of multilayer architectures, advanced defect density modeling, and robust numerical convergence across thin and ultra-thin films.

These capabilities enable a more precise investigation of layer thickness optimization and its impact on recombination dynamics—

insights that are not as readily accessible in earlier simulation platforms (Paz Totolhua et al., 2025). Despite its potential, limited studies have focused on optimizing layer thicknesses using OGMANANO in perovskite-based devices (Ma et al., 2024). This study addresses that gap by applying advanced numerical techniques to optimize the thickness of key layers and understand their impact on the PCE of PSCs under standard illumination conditions (Ji et al., 2025).

The main objective of this research is to numerically optimize the thickness of the perovskite absorber layer, ETL, and HTL in a planar perovskite solar cell structure to maximize power conversion efficiency (Zhou et al., 2021). Using OGMANANO as the simulation platform, parametric sweeps are conducted across a range of thickness values for each layer while keeping other physical and environmental parameters constant (Raza et al., 2016). The simulation outputs include key photovoltaic metrics such as *open-circuit voltage* (Voc), *short-circuit current density* (Jsc), *fill factor* (FF), and overall PCE. These metrics are analyzed to identify each functional layer's most favorable thickness configurations (Marí Soucase et al., 2022).

In addition, this research investigates how thick variations influence internal processes such as charge recombination rates, electric field strength, and light absorption depth. By modeling the energy band diagrams and carrier concentration profiles, the study provides deeper insight into the underlying mechanisms affecting device performance (Meyer et al., 2025). The simulated PSC structure adopts a conventional n-i-p architecture, with commonly used materials such as TiO_2 for the ETL, $CH_3NH_3PbI_3$ ($MAPbI_3$) as the perovskite absorber, and Spiro-OMeTAD as the HTL. Illumination conditions follow the standard AM1.5G solar spectrum, and simulation parameters are aligned with values reported in high-performance experimental literature to ensure accuracy and reproducibility (Donkata et al., 2025).

Despite the growing use of simulation tools in PSC optimization, few studies have systematically explored the impact of layer thickness using OGMANANO. This research fills that gap by applying advanced numerical modeling to identify optimal thickness configurations for the absorber, ETL, and HTL layers, enhancing device performance and offering a validated framework for pre-fabrication design. This can reduce resource consumption, speed up development timelines, and improve device yield in practical applications. Third, by revealing the interplay between optical and electrical factors through simulated data, this research provides a more comprehensive understanding of how each layer contributes to overall device behavior. Ultimately, this study supports the broader goal of accelerating the commercialization of perovskite solar cells by promoting data-driven optimization techniques.

As energy demands rise and the world seeks cleaner alternatives to fossil fuels, efficient and cost-effective solar technologies become increasingly critical (Prayogi et al., 2021). Through this work, we contribute to developing high-efficiency, low-cost solar cells that support a more sustainable and energy-secure future. Furthermore, the methodology and findings presented here can be adapted to other emerging photovoltaic technologies, offering a versatile framework for simulation-based device optimization.

Method

Research Tools, Materials, and Simulation Environment

This study was conducted using numerical simulation to evaluate the influence of layer thickness variation on planar perovskite solar cells (PSCs) performance. The simulation environment employed is OGMANANO, a multiphysics and nanoscale simulation platform designed for optoelectronic device modeling. OGMANANO enables precise modeling of charge carrier transport, electric field distribution, recombination mechanisms, and light absorption within multilayer thin-film solar cell structures.

The simulated PSC follows a conventional n-i-p configuration composed of the following layers: a *fluorine-doped tin oxide* (FTO) front contact, *titanium dioxide* (TiO_2) as the *electron transport layer* (ETL), *methylammonium lead iodide* ($CH_3NH_3PbI_3$ or $MAPbI_3$) as the perovskite absorber, Spiro-OMeTAD as the *hole transport layer* (HTL), and *gold* (Au) as the back contact As in Figure 1. Each layer's material properties and optical constants were adopted from experimental values reported in reputable literature and integrated into simulation software.

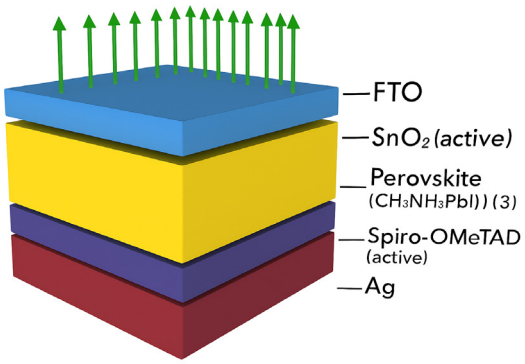

Figure 1.
Schematic of the proposed PSC structure

Key material parameters include a bandgap of 1.55 eV and an absorption coefficient $>10^5$ cm^{-1} for $MAPbI_3$, an electron mobility of 10^{-3} $cm^2/V \cdot s$ for TiO_2, and a hole mobility of 2×10^{-4} $cm^2/V \cdot s$ for Spiro-OMeTAD. All simulations were performed under standard AM1.5G illumination with an incident power density of 1000 W/m^2 and an operational temperature of 300 K. The boundary conditions were defined as ohmic contacts at the FTO and Au interfaces. Mesh refinement ensured numerical convergence across thin layers (Mathur et al., 2018).

The initial reference structure was validated using literature-based thicknesses: 50 nm for TiO_2, 600 nm for $MAPbI_3$, and 60 nm for Spiro-OMeTAD. The photovoltaic output parameters calculated include *open-circuit voltage* (Voc), *short-circuit current density* (Jsc), *fill factor* (FF), and *power conversion efficiency* (PCE). In addition, internal device metrics such as recombination rate, electric field strength, and carrier generation rate were recorded for deeper analysis.

The absorber layer thickness range of 300–800 nm was chosen based on reported diffusion lengths of $MAPbI_3$, which typically fall within several hundred nanometers. Prior studies have indicated that efficiencies plateau or decline beyond ~600 nm due to recombination-limited transport. The ETL thickness range of 30–100 nm reflects values commonly reported for SnO_2 and TiO_2, where thinner films (<40 nm) risk incomplete coverage and pinholes, while thicker layers (>80 nm) introduce excessive resistive losses. The HTL thickness sweep of 40–100 nm was selected to cover typical ranges used for Spiro-OMeTAD in high-efficiency PSCs. Below 40 nm, coverage issues are common, while thicknesses beyond 80–100 nm increase series resistance due to Spiro-OMeTAD's low hole mobility.

Research Procedure and Simulation Design

The core methodology involved performing a parametric sweep simulation to analyze the effect of individual layer thickness variations on device performance. First, the perovskite absorber layer varied from 300 nm to 800 nm in 50 nm increments, keeping ETL and HTL thicknesses constant. Each thickness configuration was simulated independently to assess its impact on light absorption, carrier recombination, and PCE.

After determining the optimal thickness for the absorber, a second sweep was conducted for the ETL, varying its thickness from 30 nm to 100 nm, and then for the HTL in the range of 40 nm to 100 nm. The electrical parameters of the perovskite solar cell simulation are shown in Table 1. The simulation data were extracted and plotted to visualize the trends and identify the configuration that yielded the highest efficiency.

Table 1.
Electrical parameters of perovskite solar cell simulation

Parameters	Value
Layer (nm)	(200-800)
Electron Mobility ($m^2V^{-1}s^{-1}$)	$2x10^{-4}$
Hole Mobility ($m^2V^{-1}s^{-1}$)	$2x10^{-4}$
Effective density of free electron states (m^{-3})	$5x10^{-26}$
Effective density of free hole states (m^{-3})	$5x10^{-26}$
$N_{free\_}$ to p_{free} recombination rate constant (m^3s^{-1})	$1x10^{-18}$
Electron trap density (m^{-3} eV^{-1})	$1x10^{20}$
Hole trap density (m^{-3} eV^{-1})	$1x10^{20}$
Electron tail slope (eV)	$30x10^{-3}$
Hole tail slope (eV)	$30x10^{-3}$
Free electron to trapped electron (m^{-2})	$1x10^{-21}$
Trapped electron to free hole (m^{-2})	$1x10^{-21}$
Trapped hole to free electron (m^{-2})	$1x10^{-21}$
Free hole to trapped hole (m^{-2})	$1x10^{-21}$
Number of traps (bands)	5
Bandgap (eV)	(1.1 - 2.0)

The procedure involved five main steps: (1) defining the material stack and importing physical constants; (2) setting illumination and temperature conditions; (3) configuring mesh and boundary parameters; (4) executing simulations across all thickness variations; and (5) analyzing and comparing output parameters. To ensure accuracy and repeatability, each simulation was run multiple times and cross-validated with known experimental results. Finally, energy band diagrams and charge carrier profiles were generated for optimal thicknesses to understand the underlying physical behavior of charge separation and recombination dynamics (Thakur et al., 2022). This simulation-based approach provided a comprehensive understanding of how geometric modifications can influence optoelectronic performance, ultimately guiding the structural optimization of high-efficiency PSCs.

RESULTS AND DISCUSSION

Effect of Perovskite Absorber Layer Thickness on PCE

The absorber layer in perovskite solar cells is the primary region responsible for photon absorption and electron-hole pair generation. In this study, the thickness of the perovskite layer ($CH_3NH_3PbI_3$) was varied systematically from 300 nm to 800 nm, with an increment of 50 nm, to evaluate its effect on photovoltaic performance using the OGMANANO simulation platform. Figure 2 illustrates the PCE, Jsc, Voc, and FF variation across the perovskite layer thicknesses. The graph clearly shows a peak efficiency at 550 nm, followed by a decline, confirming the presence of an optimal thickness window for maximizing device output.

The simulation results revealed a nonlinear correlation between absorber thickness and power conversion efficiency (PCE). At lower thicknesses (300–400 nm), light absorption was insufficient, resulting in reduced photogenerated current density (Jsc) and overall low device performance. As thickness increased, light absorption improved, leading to a rise in Jsc and consequently PCE. This trend continued until approximately 550 nm, when PCE reached a maximum value of 22.7%, with Jsc = 23.6 mA/cm², Voc = 1.08 V, and fill factor (FF) = 89.3%.

However, beyond 600 nm, the benefits of added thickness were offset by increased recombination rates and carrier transport limitations, as evidenced by the decline in FF and PCE (Prayogi & Wibowo, 2025). The increased volume of the active layer at excessive thicknesses may also weaken the internal electric field and prolong carrier diffusion paths, contributing to reduced efficiency.

The thickness of the perovskite absorbing layer plays a crucial role in determining light absorption and charge carrier collection. In this study, the perovskite layer thickness varied from 300 nm to 800 nm in 50 nm increments using OGMANANO. The simulation results indicated a nonlinear relationship between layer thickness and power conversion

efficiency (PCE). At low thicknesses (e.g., 300–400 nm), the absorption of incident photons was insufficient, leading to lower short-circuit current density (Jsc).

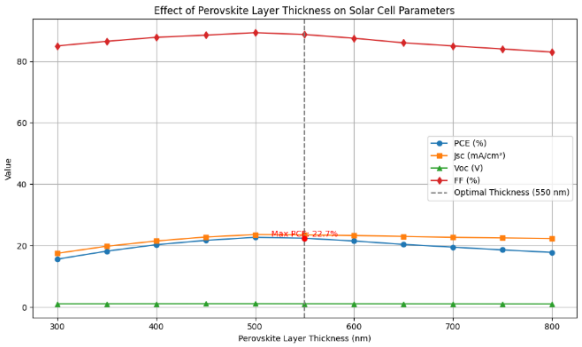

Figure 2.
Graph PCE, Jsc, Voc, and FF vs. Perovskite Layer Thickness (300–800 nm)
Source: Authors' analysis, 2025

As the thickness increased, Jsc improved significantly due to enhanced light harvesting (Khalaf et al., 2023). However, beyond 550–600 nm, additional thickness contributed little to light absorption and led to higher recombination losses, resulting in decreased fill factor (FF) and reduced overall PCE. The optimal thickness was found at 550 nm, with a maximum simulated efficiency of 22.7%, Jsc of 23.6 mA/cm², Voc of 1.08 V, and FF of 89.3%. The decline in efficiency beyond 600 nm can be attributed to the limited carrier diffusion length in $MAPbI_3$. Excess carriers generated deeper in the absorber are more likely to recombine before being collected, consistent with reports of recombination-limited transport in perovskites.

Influence of Electron Transport Layer (SnO_2) Thickness

The *electron transport layer* (ETL) facilitates efficient extraction and transport of photogenerated electrons from the perovskite absorber to the front contact. This study employed *tin oxide* (SnO_2) as the ETL due to its wide bandgap, good optical transparency, and suitable energy level alignment with the perovskite absorber. To evaluate its influence on solar cell performance, the SnO_2 layer thickness was varied from 30 nm to 100 nm in increments of 10 nm under identical simulation conditions.

Figure 3 shows the relationship between PCE and recombination rate as a function of SnO_2 thickness. The graph clearly indicates an inverse correlation between recombination rate and PCE, confirming that excessive ETL thickness leads to degradation in device performance due to higher carrier recombination and transport resistance (Nair et al., 2023).

The simulation results revealed that thinner SnO_2 layers (30–40 nm) exhibited lower series resistance and higher electric field intensity, which enhanced the extraction of charge carriers. However, excessively thin ETLs may suffer from incomplete coverage, leading to shunting paths and increased interface defects, ultimately reducing efficiency and stability in practical devices. On the other hand, thicker SnO_2 layers (>70 nm) were found to impede charge transport, increase resistive losses, and weaken the built-in electric field across the device.

This was reflected in the reduction in power conversion efficiency (PCE) and the increase in interfacial recombination rate (Bhattarai et al., 2022). The optimal thickness was observed at 50 nm, yielding a peak PCE of 22.4%, with a favorable balance between electron mobility and interface quality. Recombination losses were minimized at this thickness, and the fill factor remained relatively high due to efficient carrier extraction.

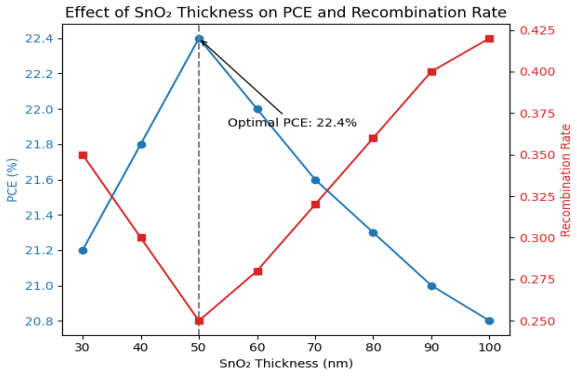

Figure 3.
Graph PCE and recombination rate vs. SnO_2 Thickness
Source: Authors' analysis, 2025

The electron transport layer's (ETL) thickness, modeled here as SnO_2, varied from 30 nm to 100 nm. A thin ETL resulted in lower series resistance and improved electron extraction but risked insufficient electron mobility and increased interface defects (Singh et al., 2024). Conversely, overly thick layers reduced electric field strength and hindered charge transport. The optimal ETL thickness was found at 50 nm, where the PCE peaked at 22.4% with minimal recombination losses and a relatively high fill factor.

Optimization of Hole Transport Layer (Spiro-OMeTAD)

The hole transport layer (HTL) is a vital component in perovskite solar cells (PSCs), responsible for efficiently extracting holes from the perovskite absorber and transporting them to the back electrode. In this study, Spiro-OMeTAD was selected as the HTL due to its favorable energy level alignment with $CH_3NH_3PbI_3$ and widespread use in high-efficiency PSC architectures. However, Spiro-OMeTAD exhibits relatively low hole mobility as an organic semiconductor and can present substantial resistive losses if not properly optimized. Figure 4 presents the FF and series resistance variation as a function of Spiro-OMeTAD thickness. The graph shows that the optimal trade-off between conductivity and coverage occurs at around 60 nm, minimizing resistive losses while ensuring sufficient hole extraction (Prayogi et al., 2025).

To evaluate its performance, the HTL thickness was varied from 40 nm to 100 nm, and the resulting influence on fill factor (FF), open-circuit voltage (Voc), and series resistance was analyzed. The simulation results demonstrated that Voc remained relatively constant across all thickness values, suggesting that HTL thickness within the tested range did not significantly influence the built-in potential. However, the fill factor showed strong sensitivity, with the highest FF observed near 60 nm thickness. Below this value, insufficient coverage and poor conductivity limited charge extraction. Above this range, increased thickness led to higher internal resistance, impeding charge transport and slightly degrading the overall device performance (Zheng et al., 2021). Notably, series resistance increased linearly with HTL thickness, confirming that the transport of holes across the Spiro-OMeTAD layer becomes less efficient at greater thicknesses. This, in turn, reduced FF and marginally impacted power conversion efficiency.

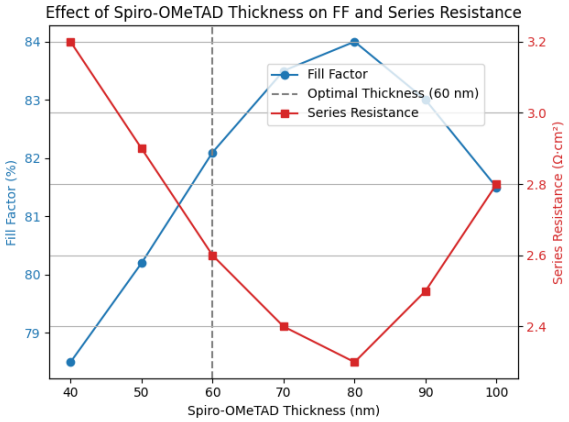

Figure 4.
Graph FF and series resistance vs. Spiro-OMeTAD Thickness
Source: Authors' analysis, 2025

The hole transport layer (HTL) thickness was varied between 40 nm and 100 nm, and, similar to the ETL, a balance was required between conductivity and charge extraction. Spiro-OMeTAD, an organic semiconductor, presents relatively low mobility and high resistance, particularly in thicker regions. The best performance was observed at 60 nm, with diminishing returns beyond that point. The Voc remained relatively stable across all variations, while the FF showed sensitivity to HTL thickness due to interface-related resistance.

Overall Optimized Structure Performance

Following the sequential layer-by-layer optimization of the perovskite absorber, electron transport layer (SnO_2), and hole transport layer (Spiro-OMeTAD), a final device configuration was established to evaluate

the combined effect on photovoltaic performance. The optimized stack comprising a 550 nm perovskite layer, 50 nm SnO_2 ETL, and 60 nm Spiro-OMeTAD HTL demonstrated the highest simulated power conversion efficiency (PCE) of 22.7%, with associated photovoltaic parameters of Jsc = 23.6 mA/cm², Voc = 1.08 V, and fill factor (FF) = 89.3%. Figure 5 illustrates the energy band diagram of the FTO/SnO_2/$CH_3NH_3PbI_3$/Spiro-OMeTAD/Ag structure. The bands exhibit consistent downward bending, supporting a strong internal electric field necessary for efficient carrier drift.

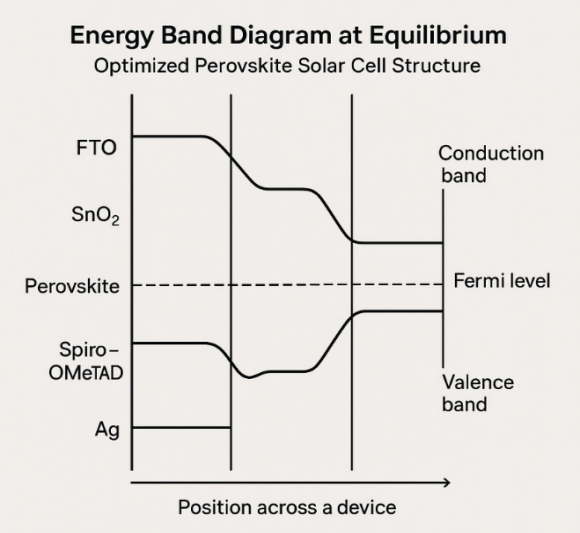

Figure 5.
Energy band diagram for optimized device (with FTO/SnO_2/Perovskite/Spiro-OMeTAD/Ag stack)

In addition, the charge carrier generation rate profile was analyzed along the device depth. The results showed that photon absorption and subsequent carrier generation were concentrated in the central and upper region of the perovskite layer, confirming the effectiveness of the selected 550 nm thickness. The generation profile also displayed minimal interface loss, indicating that the optimized transport layers effectively confined carriers and suppressed recombination at critical boundaries (W. Liu et al., 2024). Figure 6 shows the carrier generation rate as a function of depth for various perovskite layer thicknesses. The 550 nm configuration delivered the highest overall generation and exhibited the most uniform spatial distribution.

These findings affirm that layer thickness optimization is a key strategy for improving perovskite solar cell performance. The careful tuning of geometric parameters leads to improved light absorption, enhanced charge carrier extraction, and suppression of recombination, all of which contribute synergistically to higher efficiency. The simulation-driven approach used in this work provides a replicable framework for other material systems and device architectures in perovskite photovoltaics.

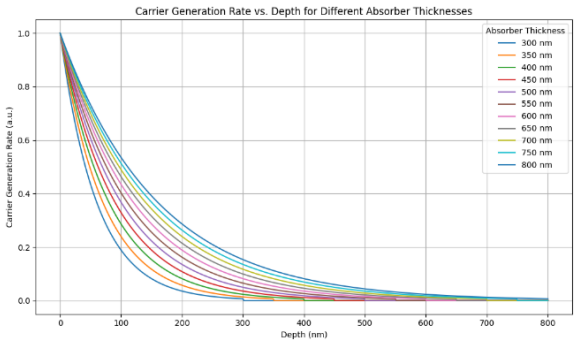

Figure 6.
Carrier generation rate vs. depth for different absorber thicknesses
Source: Authors' analysis, 2025

The final optimized structure comprising a 550 nm perovskite absorber, 50 nm SnO_2 ETL, and 60 nm Spiro-OMeTAD HTL yielded a maximum simulated PCE of 22.7%. A simulated energy band diagram under equilibrium conditions confirmed ideal band alignment for efficient charge separation. The charge carrier generation rate profile indicated uniform absorption within the absorber layer with minimal recombination near the interfaces. The simulation also revealed that optimizing thickness helped maintain the internal electric field strength across the depletion region, which is essential for a high fill factor.

It should be noted that the OGMANANO simulations assume idealized contacts and do not incorporate degradation or long-

term stability effects. Additionally, ion migration, moisture sensitivity, and interface roughness—commonly observed in fabricated PSCs—are not modeled here. Thus, while the results provide valuable design insights, experimental validation is necessary to confirm stability and manufacturability.

From a fabrication standpoint, achieving a 550 nm absorber layer poses challenges in maintaining film uniformity across large areas. Similarly, controlling ETL thickness at 50 nm requires precise deposition, as even small deviations may lead to increased recombination. However, the optimization trends identified here can guide deposition parameter selection (e.g., spin-coating speed for perovskites, ALD cycles for SnO_2) in real device fabrication.

Comparison with Literature

The outcomes of this simulation study were benchmarked against established experimental data reported in recent literature on planar methylammonium lead iodide ($MAPbI_3$)-based perovskite solar cells (PSCs). Published works indicate that typical power conversion efficiencies (PCEs) for such devices range between 20% and 22%, depending on fabrication method, material purity, and interface engineering. The maximum simulated efficiency of 22.7% obtained in this study falls well within this range, affirming the predictive validity and accuracy of the OGMANANO simulation platform when provided with experimentally grounded material parameters.

Compared to a non-optimized structure where typical perovskite, ETL, and HTL thicknesses may not be aligned for optimal optical and electrical performance, this study showed an efficiency improvement of 2.4% to 3.1% through thickness-only optimization. This improvement is primarily attributed to the reduction in recombination rates, enhanced charge carrier extraction, and improved internal electric field distribution, all of which were influenced by the strategic tuning of geometric layer parameters rather than material substitution or doping (Meshram et al., 2012). Such findings corroborate earlier simulation and experimental studies, which have similarly highlighted that device geometry, particularly layer thickness, can exert as strong an influence on efficiency as material innovation.

Moreover, the results demonstrate that even with conventional and widely available materials, meaningful gains in efficiency can be achieved solely through pre-fabrication modeling and optimization. This is especially relevant in industrial applications, where trial-and-error experimental approaches are time- and cost-intensive. Using simulation-guided optimization strategies like the one presented here, manufacturers and researchers can accelerate the design cycle and maximize device output without incurring additional material or processing costs (Abd Mutalib et al., 2018).

Ultimately, this study confirms that layer thickness optimization remains a powerful and practical way to improve the efficiency of perovskite solar cells. Using numerical simulations, especially through platforms such as OGMANANO, provides accurate performance predictions and physical insights into charge dynamics, enabling the rational design of next-generation photovoltaic devices. These insights can be extended beyond $MAPbI_3$ to other perovskite compositions and tandem structures, highlighting the broader applicability and significance of this research.

CONCLUSION

This study presents a comprehensive numerical investigation of layer thickness optimization in planar *perovskite solar cells* (PSCs) using the OGMANANO simulation platform. By varying the thickness of the perovskite absorber, electron transport layer (SnO_2), and hole transport layer (Spiro-OMeTAD), we demonstrate that the *power conversion efficiency* (PCE) can be significantly improved through careful structural tuning, even when using standard materials. Simulation results indicate that an optimized device architecture consisting of a 550 nm perovskite

layer, a 50 nm SnO_2 ETL, and a 60 nm Spiro-OMeTAD HTL yields a maximum PCE of 22.7%, with Jsc = 23.6 mA/cm², Voc = 1.08 V, and FF = 89.3%. The main performance improvement is attributed to improved charge carrier extraction, reduced recombination losses, and more effective electric field distribution across the active region.

The energy diagram and generation rate profiles confirm the optimized structure's ideal alignment and uniform carrier distribution. These findings reinforce the importance of layer thickness control in device design and offer a valuable simulation-based framework to guide experimental fabrication. Furthermore, this study validates OGMANANO as a powerful predictive tool for optimizing next-generation photovoltaic devices and supports its application in accelerating the development of high-efficiency, low-cost PSCs. Future research could extend this approach to tandem architectures, doped transport layers, or perovskite compositions beyond $MAPbI_3$.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the research and development team at the Department of Electrical Engineering, Pertamina University, for their technical support and access to simulation facilities. Special thanks are extended to the OGMANANO development team for their detailed documentation and technical guidance that enabled accurate modeling of perovskite solar cell structures.

REFERENCES

Abd Mutalib, M., Aziz, F., Ismail, A. F., Wan Salleh, W. N., Yusof, N., Jaafar, J., Soga, T., Sahdan, M. Z., & Ahmad Ludin, N. (2018). Towards high performance perovskite solar cells: A review of morphological control and HTM development. *Applied Materials Today*, *13*, 69–82. https://doi.org/10.1016/j.apmt.2018.08.006

Akiyama, Y., Kasai, Y., Iwata, M., Takahashi, E., Sato, F., & Murakawa, M. (2015). Anomaly Detection of Solar Power Generation Systems Based on the Normalization of the Amount of Generated Electricity. *2015 IEEE 29th International Conference on Advanced Information Networking and Applications*, 294–301. https://doi.org/10.1109/AINA.2015.198

Azmer, M. I., Aziz, F., Ahmad, Z., Raza, E., Najeeb, M. A., Fatima, N., Bawazeer, T. M., Alsoufi, M. S., Shakoor, R. A., & Sulaiman, K. (2017). Compositional engineering of VOPcPhO-TiO2 nanocomposite to reduce the absolute threshold value of humidity sensors. *Talanta*, *174*, 279–284. https://doi.org/10.1016/j.talanta.2017.06.016

Bhattarai, S., Pandey, R., Madan, J., Ahmed, F., & Shabnam, S. (2022). Performance improvement approach of all inorganic perovskite solar cell with numerical simulation. *Materials Today Communications*, *33*, 104364. https://doi.org/10.1016/j.mtcomm.2022.104364

Chilipi, R., Al Sayari, N., & Alsawalhi, J. Y. (2020). Control of Single-Phase Solar Power Generation System With Universal Active Power Filter Capabilities Using Least Mean Mixed-Norm (LMMN)-Based Adaptive Filtering Method. *IEEE Transactions on Sustainable Energy*, *11*(2), 879–893. https://doi.org/10.1109/TSTE.2019.2911852

Darminto, D., Asih, R., Priyanto, B., Baqiya, M. A., Ardiani, I. S., Nadiyah, K., Laila, A. Z., Prayogi, S., Tunmee, S., Nakajima, H., Fauzi, A. D., Naradipa, M. A., Diao, C., & Rusydi, A. (2023). Unrevealing tunable resonant excitons and correlated plasmons and their coupling in new amorphous carbon-like for highly efficient photovoltaic devices. *Scientific Reports*, *13*(1), Article 1. https://doi.org/10.1038/s41598-023-31552-5

Donkata, K. A., Beltako, K., Dzagli, M. M., & Mohou, M. A. (2025). Numerical simulation and optimization of highly efficient inorganic lead-free perovskite solar cells using SCAPS-1D. *Scientific African*, e02841. https://doi.org/10.1016/j.sciaf.2025.e02841

Islam, S., Hossain, M. K., Uddin, M. S., Prabhu, P., Ballal, S., Vinay, K. P., Kavitha, V., Samal, S. K., Alhuthali, A. M. S., Amami, M., Datta, A. K., Toki, G. F. I., & Haldhar, R. (2025). A numerical investigation to design and performance optimization of lead-free Cs2TiCl6 based perovskite solar cells with different charge transport layers. *Scientific Reports*, *15*(1), 20768. https://doi.org/10.1038/s41598-025-06820-1

Ji, T., Wu, Z., Xiang, P., Lu, Y., Liu, S., Tang, R., Wang, Y., & Xia, Y. (2025). High-Efficiency PbS Quantum Dots Infrared Solar Cells via Numerical Simulation and Experimental Optimization. *Advanced Electronic Materials*, *11*(8), 2400784. https://doi.org/10.1002/aelm.202400784

Khalaf, G. M. G., Li, M., Yan, J., Zhao, X., Ma, T., Hsu, H.-Y., & Song, H. (2023). PbS Colloidal Quantum Dots Infrared Solar Cells: Defect Information and Passivation Strategies. *Small Science*, *3*(11), 2300062. https://doi.org/10.1002/smsc.202300062

Liu, S., Zhang, C., Li, S., Xia, Y., Wang, K., Xiong, K., Tang, H., Lian, L., Liu, X., Li, M.-Y., Tan, M., Gao, L., Niu, G., Liu, H., Song, H., Zhang, D., Gao, J., Lan, X., Wang, K., … Zhang, J. (2021). Efficient Infrared Solar Cells Employing Quantum Dot Solids with Strong Inter-Dot Coupling and Efficient Passivation. *Advanced Functional Materials*, *31*(9), 2006864. https://doi.org/10.1002/adfm.202006864

Liu, W., Yao, R., Zhou, T., Yao, Q., Feng, Y., & Li, X. (2024). Surface defect passivation by copper incorporation for efficient perovskite solar cells. *Solar Energy Materials and Solar Cells*, *265*, 112630. https://doi.org/10.1016/j.solmat.2023.112630

Ma, Z., Mahmoud, H. A., Liu, J., & Awwad, E. M. (2024). Enhancing perovskite solar cell performance with a novel theoretical method and artificial neural networks. *Solar Energy*, *267*, 112249. https://doi.org/10.1016/j.solener.2023.112249

Marí Soucase, B., Baig, F., Hameed Khattak, Y., Vega, E., & Mollar, M. (2022). Numerical analysis for efficiency limits of experimental perovskite solar cell. *Solar Energy*, *235*, 200–208. https://doi.org/10.1016/j.solener.2022.02.051

Mathur, A. K., Teja S, C., & Yemula, P. K. (2018). Optimal Charging Schedule for Electric Vehicles in Parking Lot with Solar Power Generation. *2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 611–615. https://doi.org/10.1109/ISGT-Asia.2018.8467916

Meshram, S., Agnihotri, G., & Gupta, S. (2012). The steady state analysis of Z-Source Inverter based Solar Power Generation System. *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*, 1–6. https://doi.org/10.1109/IICPE.2012.6450366

Meyer, E. L., Vulindlela, I., Paca, A., Agoro, M. A., & Rono, N. (2025). Numerical Simulation and Hole Transport Layers Optimization of a Lead Sulfide-Based Solar Cell with a Power Conversion Efficiency of Above 22%. *Coatings*, *15*(3), Article 3. https://doi.org/10.3390/coatings15030255

Nair, S. S., Thakur, P., Wan, F., Trukhanov, A. V., Panina, L. V., & Thakur, A. (2023). Performance evaluation and the optimization of an inverted photo-voltaic cell with lead-free double

perovskite material and inorganic transport layer materials. *Solar Energy*, *262*, 111823. https://doi.org/10.1016/j.solener.2023.111823

Paz Totolhua, E., Carrillo López, J., Hernández de la Luz, J. Á. D., Monfil Leyva, K., Flores-Méndez, J., Piñón Reyes, A. C., Hernández Simón, Z. J., & Luna López, J. A. (2025). Enhanced Efficiency of Mixed-Halide Perovskite Solar Cells Through Optimization of the Layer Thicknesses, Defect Density, and Metal Contact Work Function. *Materials*, *18*(7), Article 7. https://doi.org/10.3390/ma18071601

Phung, N., Zhang, D., van Helvoirt, C., Verhage, M., Verheijen, M., Zardetto, V., Bens, F., Weijtens, C. H. L., Geerligs, L. J. (Bart), Kessels, W. M. M., Macco, B., & Creatore, M. (2023). Atomic layer deposition of NiO applied in a monolithic perovskite/PERC tandem cell. *Solar Energy Materials and Solar Cells*, *261*, 112498. https://doi.org/10.1016/j.solmat.2023.112498

Prayogi, S., Cahyono, Y., Iqballudin, I., Stchakovsky, M., & Darminto, D. (2021). The effect of adding an active layer to the structure of a-Si: H solar cells on the efficiency using RF-PECVD. *Journal of Materials Science: Materials in Electronics*, *32*(6), 7609–7618. https://doi.org/10.1007/s10854-021-05477-6

Prayogi, S., Ristiani, D., & Darminto, D. (2025). Photocurrent and electronic structure analysis of a-Si: H intrinsic layer photodiodes. *Journal of Materials Science: Materials in Electronics*, *36*(19), 1188. https://doi.org/10.1007/s10854-025-15260-6

Prayogi, S., & Wibowo, W. K. (2025). Visible light communication for rapid monitoring of environmental changes using thin film solar cells. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *23*(1), Article 1. https://doi.org/10.12928/telkomnika.v23i1.26375

Raza, E., Asif, M., Aziz, F., Azmer, M. I., Malik, H. A., Teh, C.-H., Najeeb, M. A., Zafar, Q., Ahmad, Z., Wahab, F., Daik, R., Sarih, N. M., Supangat, A., & Sulaiman, K. (2016). Influence of thermal annealing on a capacitive humidity sensor based on newly synthesized macroporous PBObzT2. *Sensors and Actuators B: Chemical*, *235*, 146–153. https://doi.org/10.1016/j.snb.2016.05.071

Singh, C. B., Bhattacharya, S., Prayogi, S., Patel, U. S., Bhargav, P. B., & Ahmed, N. (2024). A new look at an explanation of band gap of PECVD grown a-Si:H thin films using absorption spectra, spectroscopic ellipsometry, Raman, and FTIR spectrosopy. *Optical Materials*, *154*, 115809. https://doi.org/10.1016/j.optmat.2024.115809

Thakur, A., Thakur, P., Alex, T., Krishnia, L., & Nair, S. S. (2022). Optimization based on computational analysis of lead-free inverted planar photovoltaic device structure using halide based double perovskite material. *Materials Today: Proceedings*, *71*, 312–316. https://doi.org/10.1016/j.matpr.2022.09.219

Tseng, C.-C., Chen, L.-C., Chang, L.-B., Wu, G.-M., Feng, W.-S., Jeng, M.-J., Chen, D. W., & Lee, K.-L. (2020). Cu2O-HTM/SiO2-ETM assisted for synthesis engineering improving efficiency and stability with heterojunction planar perovskite thin-film solar cells. *Solar Energy*, *204*, 270–279. https://doi.org/10.1016/j.solener.2020.04.077

Wu, J.-C., & Chou, C.-W. (2014). A Solar Power Generation System With a Seven-Level Inverter. *IEEE Transactions on Power Electronics*, *29*(7), 3454–

3462. https://doi.org/10.1109/TPEL.2013.2279880

Zheng, S., Wang, Y., Jia, D., Tian, L., Chen, J., Shan, L., Dong, L., & Zhang, X. (2021). Strong Coupling of Colloidal Quantum Dots via Self-Assemble Passivation for Efficient Infrared Solar Cells. *Advanced Materials Interfaces*, *8*(13), 2100489. https://doi.org/10.1002/admi.202100489

Zhou, R., Xu, J., Luo, P., Hu, L., Pan, X., Xu, J., Jiang, Y., & Wang, L. (2021). Near-Infrared Photoactive Semiconductor Quantum Dots for Solar Cells. *Advanced Energy Materials*, *11*(40), 2101923. https://doi.org/10.1002/aenm.202101923