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Research Article

Examining the effect of temperature and thicknesss on polycrystalline semi-conductor CIGS solar cell

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ABSTRACT

Solar panels can convert the sunlight into electricity, which can be used in industry and homes. Using sunlight which is solar energy is the most plenty renewable energy sources on Earth. We acknowledge the criticism regarding the lack of clarity about the innovation in our article. The main objective of this study is to provide a detailed analysis of the factors influencing the performance of CIGS solar cells, specifically focusing on the impact of temperature and thickness on efficiency of solar cell. SCAPS 1D which is a numerical simulation software that (simulating the electrical properties of thin film heterojunction solar cells, considering both DC and AC characteristics.) has been used in this study of copper indium gallium selenide (CIGS) solar cell. In this investigation, the effect of temperature and thickness on efficiency of the solar cells has been investigated. The measurements have been shown and discussed using SCAPS 1D version 3.3.11. The experiment result clearly observed that temperature and thickness diversity directly affect the efficiency of CIGS solar cell. These parameters have been used for CIGS solar cell by electrical properties of I-V measurements. These measurements provide a critical snapshot of the cell's performance under varying operating conditions. By analyzing the I-V curves at different temperatures and thicknesses, the experiment gathered empirical evidence to corroborate our theoretical understanding. The efficiency value for indium gallium selenide (CIGS) solar cell at 300K (Working point of SCAPS 1D is 300 K and this temperature serves as a convenient reference point for calibrating and comparing models, establishing a consistent starting point for further simulations.) has been found optimum value 10.88%. This study showed that as temperature and thickness rises from 200 K to 350 K and from 1 μm to 5 μm, the efficiencies of solar cell decrease from 17.2% to 7.5% for CIGS respectively.

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INTRODUCTION

Energy is essential for life. It is the driving force behind all physical and biological processes. Energy is the very foundation of our modern world, indispensable for powering our homes, businesses, and the vital services that keep us healthy and informed. Renewable energy is an energy which comes from natural environment, such as rain, sunlight, wind, geothermal heat, waves, tides. That is crucial since renewable energy sources can help us to meet our growing energy needs while decreasing our reliance on fossil fuels and struggling climate change. Renewable energy sources most common wind, sunlight is free all over the world, and they can be used to generate electricity 24/7. Solar panels can convert the sunlight into electricity, which can be used in industry and homes. There are many studies about solar energy.

Govindasamy and Kumar. [1] performed an experiment for rising the effectiveness of solar cells using composite materials with phase change. They examined that solar panel efficiency decreases as temperature increases. Phase change materials (PCMs) can be used to keep solar panels cool, which improves their efficiency. PCMs are substance that is able to absorb and set free heat at a specific temperature. When used in solar panels, PCMs can help to keep the panels cool, which improves their efficiency. They used four different PCMs. Paraffin jelly alone, Paraffin jelly with expanded perlite, Paraffin jelly expanded graphite, Parafin jelly expanded vermiculite. The study found that the paraffin jelly with expanded perlite PCM was reduced the biggest surface temperature of the solar units by 10.29 °C. It also increased the electrical efficiency of the solar panels by 2.92% and the power output by 8.04%. The results showed that the paraffin jelly with expanded perlite PCM was the most effective at reducing the temperature and improving the efficiency of the solar panels.

Guesmi et al. [2] investigated CCTS-based solar cell's performance, which have received less attention than CZTS-based solar cells. The CCTS thin film was formed in substrate of glass by thermal evaporation and then operated on SCAPS 1D software to simulate the acts of a CCTS based solar cell. It was found that the CCTS film had big coefficient of absorption is 104 and energy of bandgap is 1.4 eV. This means that the CCTS film is able to absorb considerable part for solar spectrum, which leads to an improved conversion of photons into electricity and a new photovoltaic structure was modeled that included CCTS as the absorber material. The CCTS cell performed significant efficiency of conversion is 14.76% afterwards fixing of the absorber layers and buffers. This effectiveness was comparable to that of high-efficiency solar cells, which suggests that CCTS-based solar cells have the potential to be a viable technology for commercial applications.

Zhao et al. [3] showed to make high efficiency silicon heterojunction solar cells (SHJ) through united theoretical works and investigational works. They first optimized the Si-based thin-film layers and then implemented electrodes with rised use of indium and silver. They also used up-to-date opto-electrical simulations to find clear paths for device design and experimental optimizations. They produced FBC and SHJ solar cells at the same time monofacial solar cell and bifacial solar cell the values with the best efficiencies is 24.18% and 23.25%. They introduced various articles SHJ based solar cell architectures and found that the biggest efficiency of 27.60% can be experimentally for FBC and SHJ solar cells.

Gopal and Subash. [4] investigated the performance of mono-crystalline and poly-crystalline solar panels at Hyderabad latitude 17.43° N, 78.43° E from February to May 2018 and on April 1, 2023. The authors found that the SPV panels of both materials showed an 8% increase in energy output in 2023 compared to 2018. This suggests that solar panel technology has improved over the past 5 years, and that solar panels are becoming more efficient at converting sunlight into electricity. The authors also found that the wind speed had a small but measurable effect on the output power generation from the panels. At higher wind speeds, the panels generated slightly more power. This is likely due to the fact that the wind helps to cool the panels, which improves their efficiency. Overall, the study found that both mono-crystalline and poly-crystalline solar panels are viable options for solar power generation in Hyderabad. The authors recommend that consumers choose the type of panel that best suits their needs and budget.

Kim et al. [5] have developed functional polymeric HTMs that can passivate the perovskite/HTL interface. This improved both reliability and effectiveness of the device lasting for a considerable time. Perovskite solar cells (PSCs) were hopeful future posterity solar cell technology with high level of efficiency (25.7%) contrasted to silicon solar cells. Hole-transporting materials (HTMs) were a key component of PSCs that play a vital role in transporting holes from the perovskite layer to the electrode. The most common HTM used in PSCs is spiro-OMeTAD, but it had naturally low hole mobility and required doping with Li-TFSI and tBP to improve its performance. This doping decreased the wetness and heat balance of the PSC material. To develop the reliability and effectiveness of PSC, researchers are developing new HTMs. The last studies on efficient and stable devices based on HTM using functional polymers, small molecules, polymers, spiro OMeTAD. They focused on polymeric HTM and useful polymeric HTM, which have the potential to overcome the limitations of traditional HTM. In conclusion they developed functional polymeric HTM that can passivate the perovskite/HTL interface. This improved both the long-term reliability and effectiveness of the device.

Patil et al. [6] researched that developing an air-cooling system for solar panels to decrease the photovoltaic panel's temperature. They designed and attached an experimental air-cooling setup to the backside of a PV panel. They then conducted an experiment to contrast the effectiveness of the photovoltaic panels (PV) with the air-cooling system and without it. The study revealed that the air-cooling desing significantly reduced the running temperature of the photovoltaic panel. The values of photovoltaic panel temperature was reduced by 9 degrees Celsius. They also found that the air-cooling system increased the electrical properties performance of the photovoltaic panel. Photovoltaic panel's electrical energy conversion efficiency increased from 7% to 12.6%

Khan et al. [7] examined that ground-mounted solar systems required a lot of land, while rooftop-mounted solar panels could save land. However, rooftop structures could be damaged by strong winds. This study investigated how strong winds affect rooftop-mounted solar panels using computer simulations. The simulations found that the truss and mounting structure were the most sensitive to wind damage. The truss fails at a wind speed of -15 m/s, and the mounting structure fails at a wind speed of -25 m/s. The channel and column structures were more resistant to wind damage and can resist wind speeds of up to ±25 m/s without failing. The existing truss design is vulnerable to wind damage and fails at a wind speed of 7.53 m/s. The new truss design was more resilient and could resist winds of up to 35 m/s. The existing mounting structure was not reasonable for far-away areas with high wind speed. It failed at wind speeds above 25 m/s. The new mounting structure can resist winds of up to 25 m/s. The existing channel design is within the safe limit and does not require any changes. The existing column design was highly stable and could resist winds of up to 45 m/s.

Salehi et al. [8] showed that cooling photovoltaic panels with nanofluids is a new and effective way to improve their efficiency. The aluminum nanoparticle's effects on the conversion efficiency and cooling performance of photovoltaic panels were studied experimentally Nanofluids which had aluminum nanoparticles, cooled solar panels the reduction value of surface temperature was 13°C compare to water cooling. Photovoltaic panels has been cooled with aluminum nanoparticles and the power harvest and performance of solar panels increased by 13.5% and 13.7%.The improvements were ascribe to more surface area available for the exchange of aluminum nanoparticles and to the efficient heat transfer enable by aluminum nanoparticles high thermal conductivity contributed to the enhanced performance. The performance of aluminum nanoparticles in varios sort of coolants, solar panels and different concentrations are conduct further research.Investigate the stability of aluminum nanoparticles in liquid cooling and the effects of difference in surrounding temperature on their ability to boost conversion efficiency in photovoltaic panels. Overall, this study suggests that aluminum nanoparticles are a promising new technology for improving the efficiency of solar panels.

Urdiroz et al. [9] studied that how to better the bifacial solar unit's performance with rear cell (PERC) architecture and passivated emitter by texturing the glass surface and the silicon surface (solar cell). Light trapping used textured surfaces to guide light deeper into the solar cell, where it can be more efficiently converted into electricity. Radiative cooling uses the cold night sky to passively cool the solar panel, which can reduce thermal losses and improve efficiency. They found that texturing both surfaces could increase thermal power and photocurrent by 15% compared to a flat surface panels. However, they also found that the back of the panel can deliver up to 30% more power, but the thermal effects depend heavily on the setting up details and the conditions of atmosphere. In short, this research showed that texturing both surfaces of a bifacial solar panel can improve its performance, but that it is difficult to achieve optimum light shielding and radiant cooling at the same time.

Alomar et al. [10] investigated the energetic, economical, and exergetic performance of photovoltaic solar systems using fixed, individual axis, and dual axis tracking systems in the location of Zakho, Iraq. Tracking system improved the exergy, thermal, and electrical performance of photovoltaic solar panels.Tracking systems reduced thermal exergy losses. Cell temperatures were higher for PV solar panels with tracking systems due to direct exposure to solar radiation. Tracking systems increased the electrical energy gain of PV solar panels, with the maximum enhancement at 8 a.m. and 17 p.m. Tracking systems increased the annual yielded energy of PV solar panels by 19.6% for individual axis tracking and 26% for dual axis tracking compared to fixed panels. The setting up costed for tracking solar panels energy system were higher than for fixed systems, but the price of energy was lower.Tracking systems reduced CO_2 emissions by 473 tCO_2, 566 tCO_2 (single-axis), and 635 tCO_2 (dual-axis) compared to natural gas and gasoline. Overall, this study suggested that tracking systems improved the performance and economics of PV solar panels, and they also reduced CO_2 emissions.

Mirjalili et al. [11] showed that buildings used a lot of energy, and commercial-office buildings were the worst offenders. To create more sustainable cities, we need to adopt energy effectiveness tactics in the construction of buildings. Solar cells could help us to reduce energy consumption in buildings. They used architectures energy softwares to investigate a merchant building based on green construction guidelines, examining nearness of electrical cars and straightforward photovoltaic panels. The study found that these structures with solar panels on the top could reduce its energy consumption by 9%, and with straightforward photovoltaic panels on the windows, the reduction could be up to 18%. The refunding for the photovoltaic panels were estimated in 5 years and 9 months for the first part and 6 years and 2 months for the second part. With incentive policies, the payback period could be reduced to 2 months and 20 days for the first part and 3 years and 3 months for the second part. Overall, this study suggests that solar panels and transparent solar cells are promising technologies for reducing electricity consumption and costs in commercial-office buildings.

Ekinci et al. [12] studied that reducing the effectiveness of photovoltaic panels (PV) by cleaning. They used the effective of three different chemical solutions were made to clean photovoltaic panels. In this respect solution 1 was 2-propanol (5% v/v), solution 2 was ethanol (5% v/v) and solution 3 was acetone (5% v/v). First they handled a 3D printer to develop a solar panel cleaning robot after that chemical liquids were made in ideal status and used to photovoltaic panels with the cleaning robot. Studies showed that the most effective chemical solution was solution 1 which was (2-propanol), in conclusion solar panels can get dirty, which makes them less efficient. Using a cleaning robot on solar panels with a chemical solution can increase their efficiency. This method increased the power harvested from the photovoltaic panels aside 15%.

Tilmatine et al. [13] developed a cleaner gadget for photovoltaic panels. The cleaning gadget which uses corona wind generated by corona discharge plasma. The gadget was made up of a high-voltage electrode and a grounded frame electrode and also the gadget was moved with two wheels and is put a couple of millimeters over the photovoltaic panel surface. Experiment values that using sand dust showed that the gadget could achieve performance of 95% and the velocity of corona wind about 2 m/s. The pollution particles were removed from the plane of photovoltaic panels using the corona wind appeared of a 5 mm width at the bottom side of the gadget. The gadget could achieve corona wind velocity that 2 m/s and effectiveness of cleaning was 95% with 20 W used power. Overall, researchers suggest that the ionic wind solar panel cleaning device is a hopeful new technology for cleaning solar panels efficiently and with low power consumption.

Xu et al. [14] studied that solar photovoltaic panels were less efficient when their temperature was so high. Therefore, they used the way to get colder photovoltaic panels which was using the phase change materials (PCMs). Paraffin wax which is an organic phase change material (PCMs), it could cool very effectively solar photovoltaic panels and (PCMs) increased their power harvesting. Paraffin wax could lower the center temperature and the top surface of a photovoltaic panel aside 33.94 °C and also the bottom surface's center by 36.51 °C in five hours, under the condition that there is no wind, the light irradiation is 1000 W/m2 and the initial environmental temperature was 7.3 °C. As a result, paraffin wax can increase the average maximum value of harvesting power of photovoltaic panels aside 1.35 W and 1.63% maximum average efficiency.

Dambhare and Moharil. [15] examined that the energy losses when the sunlight hit the solar panel. Since not all of it is converted into electricity when solar cell absorbed the sunlight. There are some energy losses that take place during this process, the most common of which is heat generation. The heat causes the solar cell to warm up, which decreases its efficiency remarkable. They discuss the various mechanisms of energy loss in solar cells and methods for spectral correction. Spectral modification is a technique for changing the wavelength of light. Upconversion is a process in which is lower energy of two or more photons are combined to creating a higher energy photon. Downconversion involves the division of a photon with higher energy into two or more photons with lower energy. By using upconversion and downconversion, we can shift the wavelength of sunlight to match the solar cell's absorption spectrum, which can lead to increased efficiency. Overall, the spectral modification techniques that could guid to a significant reduction in the cost of photovoltaic panel technology because of spectral modification which can rising the efficiency of photovoltaic panels, that means we can generate more electricity from the same amount of sunlight. This is a promising technique for developing the effectivenes and decreasing the cost of photovoltaic panels.

Laseide and Ramere. [16] studied that solar farms are a growing source of renewable energy, but their efficiency can be reduced by high temperatures. Researchers used a method which is based on microcontroller water spraying set-up that uses a thermal check report system to optimize the process. Water spraying is a simple and effective way to cool solar panels, but it is important to optimize the process to avoid wasting water and reducing efficiency. In another words this method is a new way to spray water on solar panels that is more efficient and uses less water than previous methods. The new system uses a microcontroller to control the water flow and a temperature sensor to make sure the panels don't get too cold and this method has been shown to rise solar panel's effectiveness by over to 16.65% and decreased the construction cost.

Hatamleh et al. [17] studied that nanofluids (Nfs) are a mixture of conventional liquids and particles in the submicrometer range. They have improved properties compared to conventional liquids, particularly in terms of cooling. Nanofluids are progressively used in solar panel (SP) systems to improve efficiency. The researchers manage an experimental operation to investigate the electrical efficiency and thermal efficiency of solar panel systems with common fluids and nanofluids. They started up an artificial neural network to devise a data equation to predict nanofluids' cooling performance in solar panel systems. In conclusion is that the use of nanofluids instead of the usual working fluids can significantly improve the electrical and thermal properties of solar panels. The researchers have also developed an equation that can predict the cooling efficiency of nanofluids in photovoltaic panel systems, which can help to decrease the time and cost of future research studies.

Almarzooqi et al. [18] investigated that using of optical filters to increase the effectiveness of solar panel systems. The researchers knewn that the effectiveness of photovoltaic panels related to the panel's temperature. So they used that method that using a Plexiglas box filled with water can decrease the water's temperature until 46 °C. They also covered the top plane of the photovoltaic system that has optical filters can decrease the panel's temperature and also improves the electric harvest in conclusion that the use of Plexiglas as an optical filter has the future to rise the efficiency of photovoltaic panels. Researchers recommend that using this method in large-scale photovoltaic systems to figure out how plexiglass can increase the electrical harvest in photovoltaic centrals.

Aly and Clarke. [19] studied that using machine learning and computational fluid dynamics to calculate loads of wind on photovoltaic panels. The problem is that Windstorms can damage photovoltaic (PV) systems, most commonly single axis trackers. Currently used method is constructional codes dont perform exactly loads of wind for sun tracking systems. So the studies showed that this new approach can succumb various results from the typical method. The researchers propose stowing photovoltaic panels at a -15° angle during wind case to decrease damage. They also demonstrate that combining CFD and ML can accelerate operations (10,000 times faster) without failing. This new approach could be used to design more resilient PV systems.

Burgelman et al. [20] explain the numerical modeling requirements for polycrystalline thin-film solar cells, where deep traps and interfacial band offsets strongly affect device behavior. They implement a multilayer semiconductor model in SCAPS that solves Poisson and continuity equations while accounting for defect recombination. Simulated I-V, C-V and spectral-response curves closely match experimental CdTe and CIGS data, confirming its predictive accuracy. The study positions SCAPS as a reliable tool for thin-film solar-cell design and analysis.

Hossain et al. [21] investigate how different ETL/HTL combinations influence CsPbI3-based perovskite solar-cell architectures. They integrate DFT calculations with SCAPS-1D and wxAMPS simulations to evaluate band alignment, carrier extraction, and material thickness effects. Screening 96 configurations, they identify ITO/TiO2/CsPbI3/CBTS/Au as the best structure, achieving about 17.9% conversion efficiency. The results highlight that appropriate transport-layer selection is critical for improving perovskite-device performance.

Zare et al. [22] focus on the stability requirements of free-piston Stirling engines, where maintaining a stable limit cycle is essential for continuous operation. They derive dynamic-error equations and use a practical-stability framework to determine sufficient operating conditions. The analysis provides nine parametric constraints that ensure stable oscillations during design. These findings guide engineers in selecting feasible engine configurations early in development.

Mobini et al. [23] analyze the dynamic performance of free-piston engines by comparing hydrogen with conventional working gases. They assess closed-loop poles and phase-plane trajectories to evaluate startup behavior and oscillation characteristics. Hydrogen significantly enhances operating frequency, output power, and stability, outperforming gases like air and nitrogen. The study recommends hydrogen as an optimal working fluid when safety constraints are satisfied.

Tangestani et al. [24] develop a neural-network model to predict hydrogen generation in the water–gas-shift process. They incorporate catalytic and operating-condition inputs into the model to estimate hydrogen output accurately. The approach reduces experimental effort while maintaining high prediction capability. The results show that machine learning can capture complex kinetic behavior in hydrogen-production systems.

Bumararaja et al. [25] evaluate the thermal performance of a hybrid-nanofluid heat pipe using multiple machine-learning regression algorithms. They train models with a large experimental database covering different heat loads, flow rates, and inclination angles. The Extra-Tree regression model delivers the best accuracy, with less than 5% deviation from measurements. Their results confirm that data-driven techniques can provide reliable thermal predictions for heat-pipe systems.

Bumataria et al. [26] review recent advances in heat-pipe technologies using mono and hybrid nanofluids. They summarize fabrication approaches, nanoparticle selection, fluid concentration effects, and operational variables such as inclination and heat load. The review emphasizes significant thermal-conductivity enhancements achieved with hybrid nanofluids. Future research needs are also discussed to overcome stability and aggregation issues.

Laseinde et al. [16] examine thermal-management improvement in polycrystalline PV panels using an automated water-spray cooling system. Their microcontroller-based control strategy activates cooling to reduce cell temperature when needed. The system achieves about a 16.65% performance improvement under hot-climate conditions. Results demonstrate that cost-effective cooling can significantly boost PV electrical output.

MATERIALS AND METHODS

Numerical Methods

SCAPS 1D is a one dimensional solar cell simulation which the version is 3.3.11. This software is free to use to the Photovoltaic research association such as universities and research institutes, companies [21] [22]. The researcher can create a solar cell which can be various proterties with layers which can be seven; such as temperature, optical absorption, thickness, defect densities etc. And software is able to show that the measurements of: I-V, Q-E, C-f, C-V. Solar Cell Capacitance Simulator (SCAPS 1D) software's working fundamentals are related to steady state electron hole continuity equations and Poisson. The Poisson equation is shown in (1).

$$\frac{\partial^2\varphi(x)}{\partial x^2} + \frac{q}{\varepsilon_r\ \varepsilon_0}\left[p(x) - n(x) + N_D^+ - N_A^-(x) + p_t(x) - n_t(x)\right] = 0 \tag{1}$$

φ represents the electrostatic potential at position x , q denotes the electron charge N_D^+ indicates the number of positively charged donor atoms per unit volume which is ionized donor concentration, N_A^- represents the number of positively charged donor atoms per unit volume which is ionized acceptor density, the terms of p and n represents separately electron density and hole density, ε_0 and ε_r stands for permittivity of free space and relative permittivity of the semiconductor material, p_t represents the trapped hole density at position x, n_t stands for the trapped electron density at position x and (x) denotes the position in the x-coordinate system.

$$-\frac{\partial J_n}{\partial x} + G - R = 0 \tag{2}$$

$$-\frac{\partial J_p}{\partial x} + G - R = 0 \tag{3}$$

Equations (2) and (3) describe the steady-state continuity relations for electrons and holes. In simpler terms, they express how the concentrations of these charge carriers vary within the material over time. Such variations arise from three main processes: the inflow and outflow of carriers, their generation under illumination, and their recombination within the semiconductor. In these expressions, J_n and J_p denote the current densities of electrons and holes, respectively, R represents recombination processes (both direct and indirect), and G indicates the carrier generation rate.

$$J_n = qn\mu_n E + qD_n\frac{\partial n}{dx} \tag{4}$$

$$J_p = qn\mu_p E - qD_p\frac{\partial p}{dx} \tag{5}$$

The symbols μ_n and μ_p represent the mobilities of electrons and holes, while D_n and D_p denote their corresponding diffusion coefficients. The term E refers to the electric field acting within the semiconductor. The overall current in a semiconductor results from the combined effects of two fundamental transport mechanisms: drift and diffusion. The drift component describes the motion of charge carriers under the influence of an external electric field, whereas diffusion accounts for their movement from regions of higher concentration to lower concentration. Equations (4) and (5) express these principles mathematically for electrons and holes, respectively.

The optical absorption constant α:

$$\alpha(\lambda) = \left(A + \frac{B}{h\nu}\right)\sqrt[2]{\left(h\nu - E_g\right)} \tag{6}$$

The optical absorption coefficient (α) is a basic property that tells how much light a material can take in at different wavelengths. In solar cell studies, α plays a key role because it directly affects how well the device absorbs sunlight and turns it into electricity.

Equation (6) shows how the absorption coefficient (α) relates to the photon energy (hν) and the material's band gap (E_g). The constants A and B change from one material to another. In simple terms, α isn't a fixed value—it moves up or down depending on the energy of the incoming photons. When the photon energy goes beyond the band gap (hν > E_g), the material absorbs light strongly, creating plenty of charge carriers. But if the photon energy is lower (hν < E_g), absorption becomes weak, and the material is almost transparent to that light.In our work, this equation was used to describe how the CIGS layer absorbs light under real conditions. Considering that α changes with wavelength made the simulation more realistic and gave a clearer idea of how light actually behaves inside the cell. This also made the overall performance analysis more dependable.

Theoretical Background

Solar cell's characteristic is simply related to the I-V graph measurements. It shows that open circuit voltage (V_{OC}) , short circuit current (I_{SC}), voltage –current-power at maximum power point , fill factor (FF) and efficiency.Short circuit current (I_{SC}) is the maximum current that a solar cell can generate when its terminals are directly connected, essentially bypassing any load or resistance. In this scenario, the voltage across the cell is essentially zero. Open circuit voltage (V_{OC}) is the maximum voltage that a solar cell can produce when no current is flowing through it. It's essentially the theoretical voltage difference between the cell's positive and negative terminals under ideal conditions with no load connected. The maximum power point (P_{max}) is that the solar cell can generate its maximum power; in this case the current and voltage defines as I_{max} and V_{max}. The fill factor (FF) (7) is a parameter that in conjunction with V_{OC} and I_{SC} determines the maximum power from a solar cell. Efficiency is quantified as the quotient of P_{max} divided by the input light irradiance (E) and the surface area A_c of solar cell.

$$FF = \frac{P_{max}}{I_{SC}V_{OC}} \tag{7}$$

$$\eta = \left(\frac{FF\ x\ I_{SC}V_{OC}}{ExA_c}\right) \tag{8}$$

If you look at Figure 1, the I–V curve basically shows how a solar cell reacts when the light or temperature changes. It's the main way to see how well the cell works and where it delivers the most power. The shape of this curve isn't fixed — it varies with the type of technology used, whether that's a crystalline-silicon panel, a thin-film design, or some newer photovoltaic setup.

At the short-circuit point, the voltage drops to zero while the current reaches its peak. That's the maximum

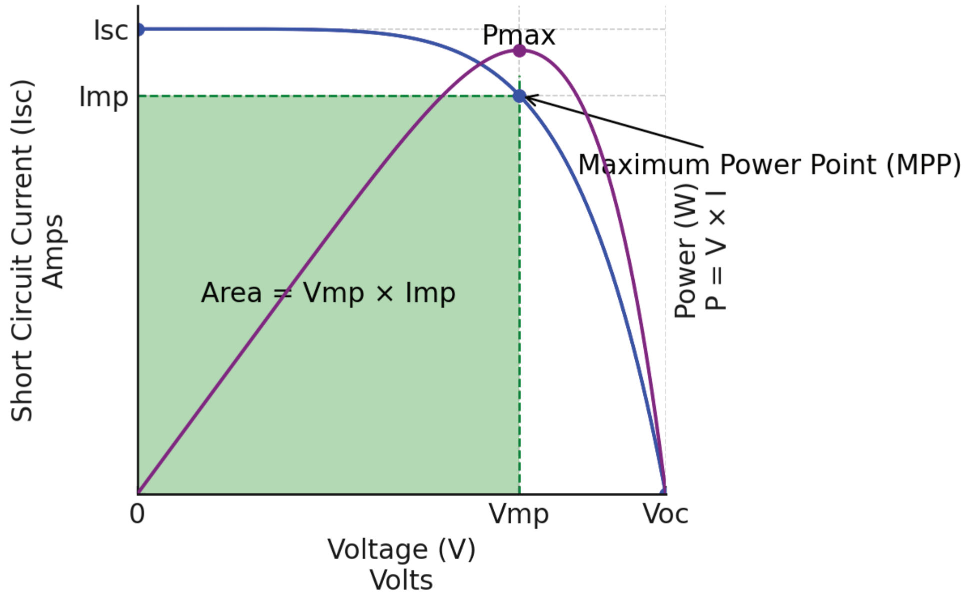

Figure 1. The solar I-V curve visually illustrates the operational behavior of a specific solar cell.

current you can get when the cell's terminals are directly linked together. In the opposite case, the open-circuit point, the current becomes zero and the voltage climbs to its highest value. This is the greatest voltage the device can produce when there's no external load connected.

Between these two limits lies what's called the **maximum power point (Pmax)** — the spot where the product of current and voltage gives the highest output. Knowing this point is crucial for figuring out how efficient the cell really is and for setting its best working conditions in practice.

Device Structure and Simulation Parameters

The development of PV technology has caused to a rise in simulation models and tools. These simulation applications can estimate and approach the simulation of monocrystalline, polycrystalline and matters based on solar cells. Among those simulation softwares, the SCAPS-1D simulator is one of the softwares withan advanced algorithm that takes into account the higher number of parameters. In this study, we used CIGS based photovoltaic panels. In figure 2 illustrates the structure's the schematic employed in this simulation.

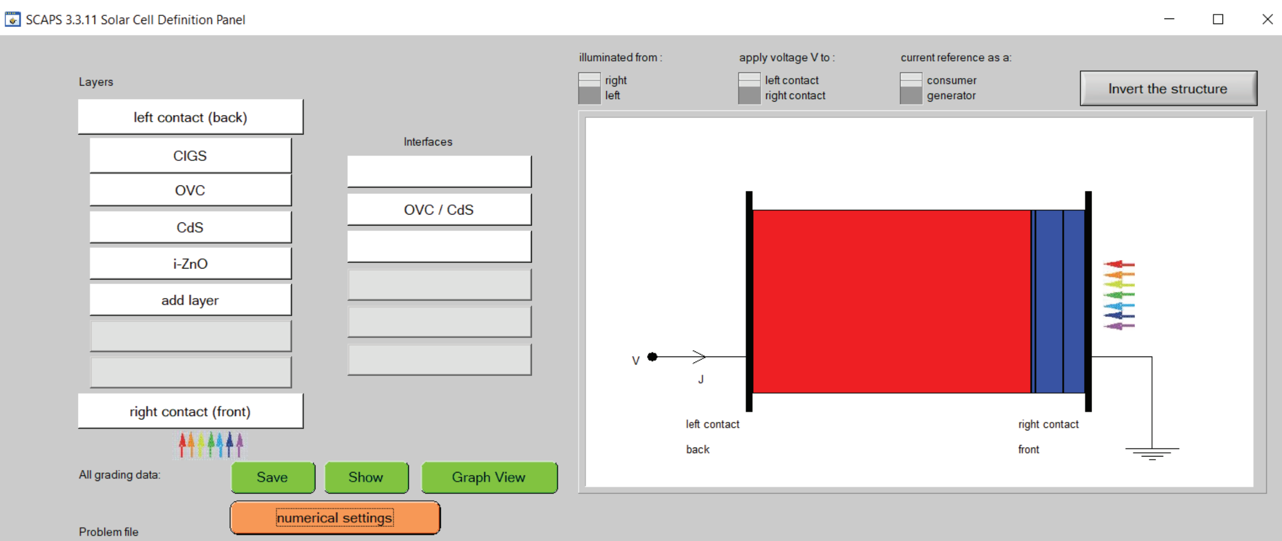

Figure 2. The model's representation that used for the Photovoltaic simulation on SCAPS 1D, four layer structures were chosen.

Table 1. Material properties date for simulating the CIGS solar cell layers

	CIGS	OVC	CdS	i-Zno
Thickness: W	1	0.015	0.100	0.080
Profil	Uniform	Uniform	Uniform	Uniform
Properties	Pure A (y=0)	Pure A (y=0)	Pure A (y=0)	Pure A (y=0)
Gap energy: E_g(eV)	1.2	1.45	2.45	3.4
Electron affinity:χ(eV)	4.5	4.5	4.45	4.55
Relative permittivity: ϵ_r (cm^{-3})	10	10	10	10
Density of state in CB: N_C (cm^{-3})	2.0×10^{18}	2.0×10^{18}	2.0×10^{18}	4.0×10^{18}
Density of state in VB: N_V (cm^{-3})	2.0×10^{18}	2.0×10^{18}	1.5×10^{19}	9.0×10^{18}
Thermale velocity of electrons: V_{thn}(cm/s)	10^7	10^7	10^7	10^7
Thermale velocity of holes: V_{thp}(cm/s)	10^7	10^7	10^7	10^7
Electrons mobility: μ_n (cm^2/V_s)	50	1	50	50
Holes mobility: μ_p (cm^2/V_s)	20	1	20	20
Density of donnors: N_D (cm^{-3})	0	10^{13}	10^{15}	5.0×10^{17}
Density of acceptors: N_A (cm^{-3})	5.5×10^{15}	0	0	0
Coefficient of absorption	sqrt(hv-Eg) law (SCAPS traditional)	sqrt(hv-Eg) law (SCAPS traditional)	sqrt(hv-Eg) law (SCAPS traditional)	sqrt(hv-Eg) law (SCAPS traditional)

The SCAPS-1D program basically works around something called a *Layers List*. It's like a stack of thin material layers that together make the solar cell. Each layer has its own job — the absorber takes in sunlight, and the contacts collect the current. When researchers change the layer settings such as thickness, doping, or defect levels, they can see how light absorption and carrier movement change. Adjusting these things helps them find a balance between better absorption and fewer recombination losses. That's how new and more efficient solar-cell structures are tested before being built.

Table 1 shows the main data used to model the Copper Indium Gallium Selenide (CIGS) cell. It lists physical and electrical properties for each layer — usually the absorber, buffer, and transparent conductor — since every one of them affects performance differently. The important numbers are the band gap, carrier mobility, lifetime, doping, and dielectric constant. For example, the band gap decides what part of sunlight the cell can absorb, while mobility and lifetime show how fast the charges move and how likely they are to recombine before reaching the contacts.

The values in Table 1 mostly come from earlier studies and standard reference data. They're not exact; they just give a realistic range. In real use, these numbers change depending on how the material is made or tested. Outdoor conditions can also shift the behavior of the cell, so the simulation results won't always match perfectly. Because of that, the parameters here should be seen as general guides, not fixed facts. As research goes on, these numbers will be updated, and the models will get closer to what really happens in working solar panels.

RESULTS AND DISCUSSION

Temperature (K) and Thickness (um) Effects

In this part of the experiment, the effects of the temperature and thickness on efficiency of the solar panel has been investigated. Table 2 demonstrated the distribution of the temperature and thickness used in this study.

To clarify the dominant parameter affecting performance, Table 2 has been examined in detail. The data obtained from Table 2, which reveals that temperature has a more significant impact on CIGS solar cell efficiency than thickness within the investigated ranges. Specifically, increasing the temperature from 200K to 350K at a constant thickness results in a substantial decrease in efficiency (around 9.7%), while varying the thickness from 1μm to 5μm at a constant temperature leads to only a minor change (around 0.02%). This highlights the critical role of temperature control in optimizing CIGS solar cell performance. Our detailed simulations, summarized in Table 2, the operated I-V parameters Jsc (mA/cm^2), Voc (V), Fillfactor FF and solar cell efficiency η (%) of single shot at different thicknesses and temperatures for indium gallium selenide (CIGS) solar cell under lighting, that the CIGS solar cell's best experiment values with open circuit voltage, short circuit current density, fill factor and efficiency is 0.558731V, 31.75017336 mA/cm^2, 61.3, and 10.8845 % at 3.0000μm and 300K respectively. However, simulation show has been showed at 300K, 1.000 μm open-circuit voltage, short-circuit current density, fill factor and efficiency is 0.558663 V, 31.68649100 mA/cm^2, 61.4 %, and 10.8697 % at same temperature and 2000 μm open-circuit voltage, short-circuit current density, fill factor and efficiency is

Table 2. I-V curve parameters simulated (*V*), (*mA/cm*^{2}), eta and FF (%) is calculated in single shot at different temperatures (*K*) and thicknesses (*μm*) for indium gallium selenide (CIGS) solar cell under lighting

Thickness (*μm*)	Temperature (*K*)	Voc	Jsc	FF	η
1.000	200	0.811174	32.51037855	65.3878 %	17.2438 %
	250	0.685849	32.17308486	64.2102%	14.1685%
	300	0.558663	31.68649100	61.4038 %	10.8697 %
	350	0.428152	31.09036540	56.5998 %	7.5342 %
2.000	200	0.811213	32.54778994	65.3738 %	17.2608 %
	250	0.685894	32.21165389	64.1904 %	14.1821 %
	300	0.558703	31.72554985	61.3798 %	10.8797 %
	350	0.428195	31.12918500	56.5702 %	7.5405 %
3.000	200	0.811233	32.57197941	65.3559 %	17.2693 %
	250	0.685918	32.23625417	64.1689 %	14.1887 %
	300	0.558731	31.75017336	61.3562 %	10.8845 %
	350	0.428221	31.15329095	56.5444 %	7.5433 %
4.000	200	0.811235	32.59043407	65.3383 %	17.2745 %
	250	0.685938	32.25452380	64.1484 %	14.1926 %
	300	0.558752	31.76825075	61.3324 %	10.8869 %
	350	0.428243	31.17090562	56.5194 %	7.5446 %
5.000	200	0.811240	32.60452643	65.3216 %	17.2776 %
	250	0.685955	32.26887439	64.1283 %	14.1948 %
	300	0.558769	31.78243479	61.3100 %	10.8881 %
	350	0.428260	31.18473481	56.4950 %	7.5450 %

0.558703 V, 31.72554985 mA/cm^2, 61.3 %, and 10.8797%. Buffing layer thickness caused to a few rise in efficiency as like, at 4.000 and 5.000 μm respectively open-circuit voltage, short-circuit current density, fill factor and efficiency is 0.558752 V, 31.72554985 mA/cm^2, 61.3 %, and 10.8869 % and 0.558769V, 31.78243479 mA/cm^2, 61.3%, and 10.8881 %. Comparing to 200K the greater values single shot at 5.000 μm is open-circuit voltage, short-circuit current density, fill factor and efficiency is 0. 811240V, 32.60452643 mA/cm^2, 65.3 %, and 17.2776 %. So these values tell us that greater values at 200K compared to 300K. The worst values compared to other temperature parameters is at 350K at 1.000 μm with open-circuit voltage, short-circuit current density, fill factor and efficiency is 0.428152V, 31.09036540 mA/cm^2, 56.5, and 7.5342 %.The performance of the CIGS solar cell was examined under various temperature and thickness conditions. The best results were obtained at 300 K with an absorber thickness of 3.0 μm, where the device produced an open-circuit voltage (Voc) of 0.5587 V, a short-circuit current density (Jsc) of 31.75 mA/cm², a fill factor (FF) of 61.3%, and an overall efficiency of 10.88%. As the temperature increased, charge carriers gained kinetic energy, which led to more frequent collisions and recombination events. This behavior caused both the current and the overall efficiency to drop. In contrast, increasing the absorber thickness improved light absorption but also raised internal resistance, resulting in additional losses. The relatively stable fill factor across all conditions reflects the electrical stability of the simulated device. Choosing 300 K as the reference temperature in SCAPS-1D simulations was not arbitrary—it reflects a balance between practicality and performance. At this temperature and thickness (3 μm), the solar cell reached its best combination of Voc, Jsc, FF, and efficiency, aligning closely with typical room-temperature conditions. Because most experimental measurements are performed near 25 °C (≈ 298 K), the difference between simulations and real-world data remains minimal. Even slight deviations—on the order of only a few millivolts in Voc—do not significantly affect accuracy. Thus, 300 K serves as a reliable benchmark for both modeling and laboratory validation. The nearly constant fill factor of about 61% further confirms that the CIGS device maintains electrical consistency across these operating conditions.

When you look closely at the results, it becomes clear which factors shape how the device behaves. The interaction between temperature and thickness is especially important because it lets engineers tweak the design of CIGS cells for better output without pushing up manufacturing costs. Temperature changes affect carrier mobility and recombination, while thickness alters how light is absorbed and how much internal resistance builds up. Getting the balance right between the two is what makes the cell perform well. Interestingly, the data around 300 K fits real industrial conditions quite well, so it serves as a good and repeatable reference point for optimization.

Efficiency, noted as η, is still the simplest way to judge how well a solar cell converts sunlight into power. When the cell heats up, η usually drops because the current–voltage (I–V) curve starts to distort. Higher temperatures lower both Voc and Isc, which means less power overall. The effect of thickness is a bit more complicated. A thicker absorber grabs more photons and raises current, but it also adds resistance and slightly pulls voltage down. Thin layers do the opposite — better voltage, weaker current. So, finding a middle ground between the two is what really pushes efficiency upward.

In general, how temperature and thickness interact sets the limits of what a CIGS device can do. The simulations here show that decent efficiency can be reached even with minimal material use, as long as structural and thermal settings are properly adjusted. The absorber layer matters the most: if it's thinner than about 3 μm, it doesn't take in enough light; if it's thicker, resistance grows and carrier flow slows down. Around 3 μm seems to be the sweet spot, since making it thicker doesn't bring much benefit.

The band gap of the absorber also plays a big role. Making the band gap wider cuts down photon absorption and current, but it slightly raises Voc because voltage scales with band gap energy. In this case, tuning the band gap carefully brought the efficiency up to roughly 17.2%, showing that band-gap engineering can really boost CIGS performance when done within realistic limits.

Overall, these findings point toward a clearer way to design efficient yet affordable CIGS solar cells. By understanding how temperature and thickness work together and adjusting material properties accordingly, it's possible to push the technology much closer to its theoretical best while still keeping production practical and cost-effective.

CONCLUSION

The CIGS solar cell was comprehensively simulated and analyzed using SCAPS-1D (version 3.3.11) under varying temperature and thickness conditions, as detailed in Table 1 and Figure 2. Among all the cases examined, the most favorable performance was achieved at 300 K with a layer thickness of 3.0 μm. Under these conditions, the device reached a short-circuit current density (Jsc) of 31.75 mA/cm^2, an open-circuit voltage (Voc) of 0.5587 V, a fill factor of 61.3%, and an efficiency of 10.88% under illumination. These results clearly indicate that both temperature and absorber thickness play decisive roles in defining the electrical response of CIGS solar cells.

To ensure the validity of our findings, we compared them with the experimental and numerical studies by Laseide and Ramere (2021) and Patil et al. (2023), both of which investigated similar temperature- and thickness-related effects on photovoltaic efficiency. The observed patterns were consistent. For instance, our simulations showed a noticeable drop in efficiency—from 17.2% to 7.5%—as the temperature increased from 200 K to 350 K, whereas Laseide and Ramere reported a comparable but smaller decline (from 14.8% to 13.5%) over a 7 °C temperature rise. This alignment not only supports the reliability of our simulation but also situates our work within a broader, experimentally validated context. By contrasting our results with those in the literature, we emphasize both the robustness of our data and the distinct contribution of this study to ongoing CIGS research.

The results show that pushing either temperature or layer thickness too far hurts the solar cell's performance. When the temperature rises too much, carrier recombination speeds up; when the absorber layer gets thicker, more defects form and internal resistance goes up. Both effects lower the open-circuit voltage (Voc) and short-circuit current (Jsc), which together drag down overall efficiency (η). To avoid that, the fabrication steps have to be carefully tuned—especially the absorber thickness and processing temperature. Keeping that balance not only improves efficiency but also makes the device more durable and easier to reproduce in manufacturing.

Our efficiency values are close to those reported in earlier work on polycrystalline cells [17], but this study looks at the combined effect of temperature and thickness over a wider range (200 K – 350 K and 1 μm – 5 μm). The data make it clear that both factors depend on each other: temperature has the stronger impact, while thickness changes the outcome more subtly but still measurably. The best results showed up again near 3 μm, confirming that making the layer any thicker adds little or no benefit.

Overall, these findings give useful direction for improving how CIGS solar cells are built and operated. Using simulation tools such as SCAPS-1D helps make sense of the complicated behavior inside multilayer solar devices. This kind of modeling links theory and real experiments, helping researchers predict performance more accurately. In the end, it can cut testing costs, speed up material development, and support cleaner, more efficient, and affordable photovoltaic systems.

NOMENCLATURE

CIGS	Copper Indium Gallium Selenide
Voc	Open-Circuit Voltage, V
Jsc	Short-Circuit Current Density, mA/cm^2
FF	Fill Factor, %
η	Efficiency, %
T	Temperature, K
μm	Micrometer
SCAPS	Solar Cell Capacitance Simulator
ZnO	Zinc Oxide
CdS	Cadmium Sulfide
Mo	Molybdenum
ITO	Indium Tin Oxide

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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