Anbar Journal of Engineering Science (AJES) **Vol. 17 , No. 1 (2026) , pp. 145 ~ 162**
P-ISSN: 1997-9428; E-ISSN: 2706-7440 DOI: http://doi.org/10.37649/AJES.26.0013

University of Anbar

Anbar Journal of Engineering Science

journal homepage: https://ajes.uoanbar.edu.iq/

Thermal effect Mitigation Strategies for Solar Cells: A Review

Marwa A. Assi[a], Mohammad Tariq Yaseen[b], Shamil H. Hussein[c]

[a]*Department of Electrical Engineering, University of Mosul, Mosul, Iraq*
Email: marwa.24enp61@student.uomosul.edu.iq ; ORCID: https://orcid.org/0009-0005-8073-2184
[b] *Department of Communications and Intelligent Digital Systems Engineering,University of Mosul, Mosul, Iraq*
Email: mtyaseen@uomosul.edu.iq ; ORCID: https://orcid.org/0000-0001-7173-8684
[c]*Department of Communications and Intelligent Digital Systems Engineering, University of Mosul, Mosul, Iraq*
Email: shamil_alnajjar84@uomosul.edu.iq ; ORCID: https://orcid.org/0000-0003-1562-5372

PAPER INFO

Paper history (8pt)
Received: 25/02/2026
Revised: 20/04/2026
Accepted: 11/05/2026

Keywords:
III-V solar cell Materials
Perovskite solar cells (PSCs)
Thermal stability of solar cells
High temperature solar cell
Wide bandgap materials.

Copyright: ©2023 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY-4.0) license.
https://creativecommons.org/licenses/by/4.0/

ABSTRACT

Solar cells are a crucial renewable resource, yet photovoltaic (PV) devices suffer performance degradation as temperatures rise (typically 0.4–0.5% per °C, reaching up to 15% under extreme heat), especially in demanding environments like deserts and space. At higher temperatures, carrier recombination becomes more pronounced, the bandgap slightly decreases, and material degradation accelerates, thereby reducing the device efficiency and long-term stability. Therefore, understanding and managing thermal effects is essential for optimizing performance and extending the lifespan of solar cells.This review discusses the latest advancements (2017–2025) in mitigating thermal impacts across various photovoltaic technologies, including thin-film solar cells, single- and multi-junction III–V cells, traditional silicon cells, and emerging perovskite and tandem structures. To address these challenges, diverse strategies have been explored, such as bandgap engineering, doping optimization, and absorber thickness control, alongside thermal management approaches like phase-change materials, cooling systems, enhanced encapsulation, and nanostructured coatings.Perovskite solar cells can exhibit improved thermal tolerance under optimized conditions compared to traditional silicon-based devices, attributed to their tunable bandgap and low temperature coefficient; they can be further adapted through material and interface engineering. Recent studies demonstrate that optimally engineered perovskite cells maintain high efficiency at elevated temperatures, making them suitable for high-temperature and demanding environmental applications. However, their long-term stability remains limited in hot conditions despite these enhancements. This review highlights deficiencies in existing research and proposes strategies for advancing the development of solar cells that are both highly efficient and thermally stable, ensuring robust performance in challenging global climates.

1. Introduction

With the rapid depletion of fossil fuels and the escalating impacts of climate change, the world is in need of advanced technologies and materials that will make energy production and storage more efficient and sustainable. As a result, a lot of research has sped up the use of renewable energy sources for the generation of electrical power [1]. Solar energy has become one of the most well-known and dependable sources of energy that can

* Corresponding author: Mohammad Tariq Yaseen; mtyaseen@uomosul.edu.iq ; +964-7736977178

meet the growing global demand for energy [2]. Photovoltaic (PV) technology is very important for using solar energy. Photovoltaic cells, which are usually made of semiconductor materials like silicon, turn sunlight directly into electricity by creating an electric field inside the cells across PN junctions [3]. The power conversion efficiency (PCE) of solar cells is one of the effective methods for evaluating their efficiency. This is still a very important part of solar cell research [4]. The device gathers sunlight, but it only produces a negligible amount of electricity [5].

One of the most critical challenges facing photovoltaic systems is that they must operate at high temperatures. As temperatures rise, solar cells become less efficient due to increased carrier recombination rates, decreased semiconductor band gaps, and reduced open-circuit voltages (Voc) and short-circuit current densities (Jsc) [6]. Photovoltaic performance is highly temperature-dependent, with power decreasing by ~0.4–0.5% per °C and reaching ~15% loss at 55 °C. Thermal stress causes electrical losses and accelerates material breakdown, which damages solar cells mechanically and reduces their lifespan [7]. The intensity of these thermal effects depends on the solar cell's design, the materials used, and how the device is assembled. Due to the significant impact of temperature on solar cell characteristics, as it reduces the lifespan of solar cells and increases the Levelized Cost of Energy (LCOE), thereby affecting the overall economic viability of photovoltaic systems. a solid understanding of solar panel technology is necessary [8].

In recent years, much research has been performed to improve the durability and efficiency of solar cells in harsh environments such as desert and space [9]. The materials with high thermal stability and large bandgap can be obtained [10]. Or the device structures can be optimized and the thickness of the absorber and the concentration of the dopant can be precisely controlled [11]. Two new methods are based on plasmonic [12] and photonic nanostructures [13] to trap the light more efficiently and prevent the charge carriers to escape. Photovoltaic devices with better encapsulation materials and radiation protective coatings have been demonstrated to have improved performance in harsh conditions [14].

The review highlights the main research works on thermal mitigation strategies of solar cells for the period of 2017-2026 covering silicon, III-V, thin-film and perovskite technologies with special focus on the recent advances and challenges. It provides a systematic comparative review. It includes advances like hybrid cooling, advanced materials and smart thermal management. Its clear assessment framework in terms of temperature drop and efficiency gains.

2. Impact of Temperature on Solar Cell Performance

The operating temperature of solar cells is an important parameter for their durability and efficiency. As the temperature increases the bandgap of the semiconductor decreases. For this reason, the Voc is the most temperature sensitive photovoltaic parameter. The Jsc can be slightly increased due to improved carrier generation rate but it is not enough to compensate the voltage drop. This brings down the overall PCE. Additionally, higher temperatures lead to more intrinsic carriers and their faster recombination, particularly at defect sites and interfaces, causing degradation in device performance. A popular way of measuring the effects of temperature on the performance of the solar cell is using the temperature coefficient. Most of the photovoltaic technologies have poor characteristics especially the crystalline silicon solar cells [15].

In addition to electrical losses, long-term operation at elevated temperatures accelerates the physical and chemical degradation of solar cells and modules . Thermal stress can cause mechanical fatigue, delamination, solder joint failure and discoloration of encapsulants. It can also accelerate ion movement and defect formation in emerging technologies such as perovskite and thin-film solar cells. In the harsh environments characterized by large temperature variations and high intensity of sunlight such as deserts or space, these degradation pathways are accelerated and severely limit the operational lifetime and reliability of solar cells. The temperature coefficient shows that crystalline silicon solar cells lose around 0.4–0.5% of their efficiency per °C, while thin-film and perovskite cells are less sensitive to heat.Thus, it becomes crucial to comprehend the temperature-dependent behaviors of various photovoltaic materials and

device architectures for the development of heat-resilient solar cells and efficient solutions [16].

Solar cells don't generate as much electricity or support development under elevated temperature conditions. As the temperature goes up, the bandgap of a semiconductor gets smaller. This makes the electric field that separates charges weaker, which decreases Voc [17]. At higher temperatures, inherent carriers are likewise more densely packed. Because of this, recombination proceeds more quickly in bulk and at the interface. Because of this, recombination will cause greater losses, a lower fill factor, and a worse power conversion efficiency [18]. Thermal stress can destroy back sheets, encapsulants, and connections between modules. It also hurts anything that need power. Things that break can alter colour, block light from flowing through, and break down chemically. Thermal cycling results in increased stress within the materials, which leads to delamination, microscopic cracks, and damage at the solder joints. These factors make the materials less stable and reliable over time. These temperature-related effects on electrical and physical systems work together to degrade the life and efficiency of solar systems when it is hot and sunny [19].

In 2025 [20], Sebastian and others used the SCAPS-1D simulator to write a long, one-dimensional numerical study of thin-film CIGS solar cells as shown in Figure 1. The team evaluated the performance of the devices under varying temperature conditions, the energy of the band gap, and how thick the absorber layer is. They increased the thickness of the absorber from 0.8 to 2.0 µm. This showed that the thicker the material, the more photons it absorbs. This makes the Jsc denser and the power conversion more efficient.

At 1.6 µm, the efficiency was highest at 15.43%. After that, bulk recombination stops any more progress as shown in Figure 2. It was clear that there was a trade-off between Jsc and Voc when we found the best band gap between 0.8 and 1.8 eV. The best band gap was between 1.3 and 1.4 eV. The increase in both voltage and current density is attributed to enhanced photon absorption and reduced recombination within the optimal band gap range. When temperatures were between 240 °K and 360 °K, simulations showed that the efficiency gradually declined as the temperature went up. Decrease in Voc and fill factor was the main reason for this. The optimized structure worked best at 240 °K, as shown in Figure 3, with an overall efficiency of 19.95%. The optimized device also had a high quantum efficiency of more than 90% between 350 and 900 nm. This means that it could pick up carriers and absorb light well over most of the solar spectrum. These results show that you need to change the thickness, band gap, and temperature all at the same time to get the most out of CIGS solar cells. Additionally, they provide valuable numerical results for making the layer that absorbs.

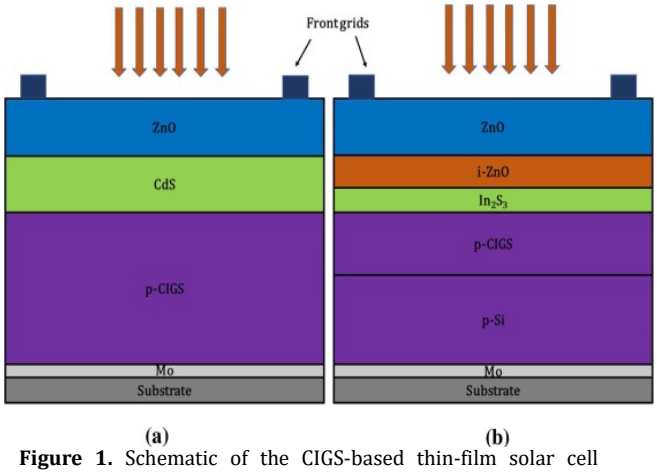


Figure 1. Schematic of the CIGS-based thin-film solar cell simulation in SCAPS-1D [20]

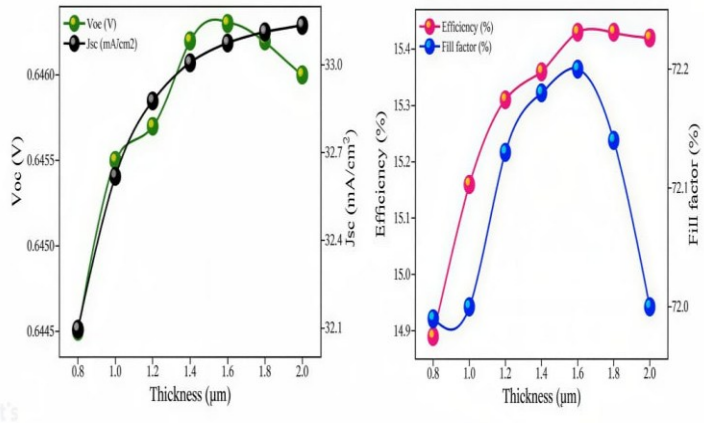


Figure 2. Simulated variation of Jsc, Voc, efficiency and FF with CIGS thickness [20]

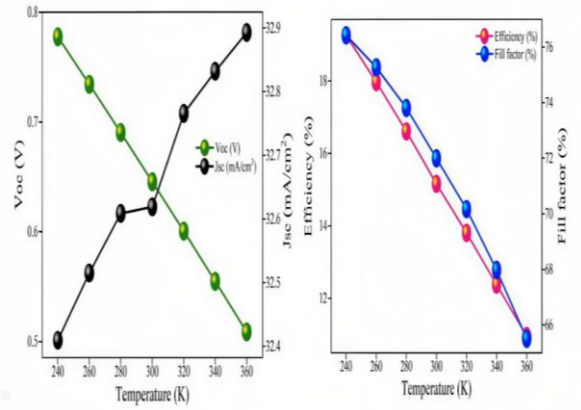


Figure 3. Simulated variation of Jsc, Voc, efficiency and FF with temperature [20]

3. Passive Thermal Mitigation Techniques

Passive thermal mitigation techniques have control operational temperature for photovoltaic systems without requiring complicated control systems or external energy. There are different methods of passive thermal mitigation that keep temperatures stable under different conditions. These methods help solar cells retain more heat, cool down faster, and get more sunlight. Passive cooling is more efficient and outperforms active cooling in terms of performance. It's better to work on a bigger scale and doesn't need that much maintenance. Thus, it is better to use it in big solar farms in remote areas. Recent research has shown that passive thermal management can prolong life of modules and retard degradation of materials while improving the efficiency of power conversion, particularly in hot and sunny regions. In the following sections some common ways to cool things down that don't require any electricity will be discussed. They include radiative cooling techniques, optical and spectral data processing systems, and phase change materials and heat sink design. A lecture about the most important problems and how to solve them [21] also will be.

3.1. Heat-sinks and extended surface structures

The most common way to cool solar cells without electricity is to use heat sinks or structures with a large surface area. These methods rely on conduction and convection to help the object cool down. "They don't have to draw any more energy." Copper and aluminum are good heat transfer materials and are often used to make heat sinks / cooling components. They are on the back of solar panels and help with heat flow. Experimental and numerical studies have shown that operating temperatures can be reduced and power output can be increased drastically by varying the configuration, spacing and orientation of the fins especially in the case of concentrator photovoltaic (CPV) systems and sunny climates. However, many of these are still difficult to use due to costs, transport limitations and compatibility with other devices [22].

A 2020 [23] study by Arifin, Zainal, and others examined how heat sink properties affect solar cell cooling systems. This study looks into how well finned heat sinks work for cooling passive solar panels as shown in Figure 4. If you use copper and add more fins, a photovoltaic system will generate more electricity and dissipate heat much more efficiently. The best configuration showed how well passive cooling keeps the panel from overheating and included 15 copper fins. The temperature was lowered by 10.2 °C and efficiency was raised by 2.74%.

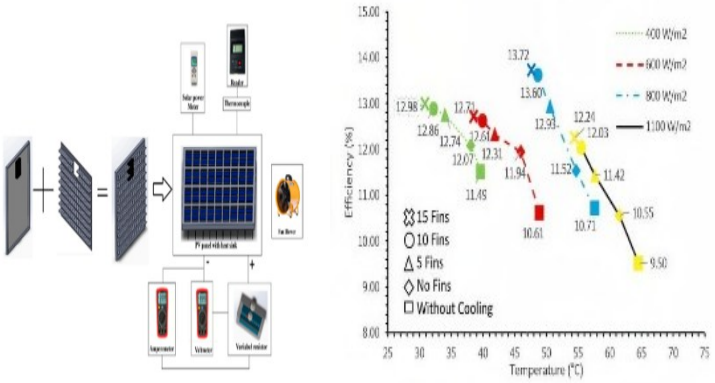


Figure 4. The solar cell system using heat-sink cooling: (a) Schematic diagram, (b) Simulated power efficiency as a function of varying temperature at different intensity [23].

3.2. Phase Change Materials (PCM)

Phase change materials (PCMs) are very popular as passive thermal regulators because they can store and collect heat when they change phases. When

PCMs are placed behind photovoltaic modules, which is when the sun is at its strongest, they keep the cell temperature close to its melting point. This keeps the temperature down. There have been many studies on bio-based PCMs, paraffin waxes, and fatty acids. These studies demonstrate that efficiency rises with a temperature reduction of 3-8°C. Scientists have used nanoparticles, metal foams, or graphite to make PCM better. Because of this, the materials stay stable over time and heat can move through them more easily [24].

Akeiber and Hussein Jassim demonstrate the application of PCMs for the cooling of solar cells in 2025 [25]. When phase change materials change phases, they use latent heat to control the temperature. This research examines the application of PCMs for the cooling of buildings, electronics, and industrial processes. The results show that adding PCM can lower the highest operating temperatures by 8 to 20 °C, use 15 to 45% less energy to cool, and lower temperature swings by as much as 30 to 50%. Thermal energy storage can store two to four times as much energy as sensible heat storage. Nano-enhanced and composite PCMs also improve thermal conductivity by 200% to 500%, which means that Heat can dissipate more rapidly.

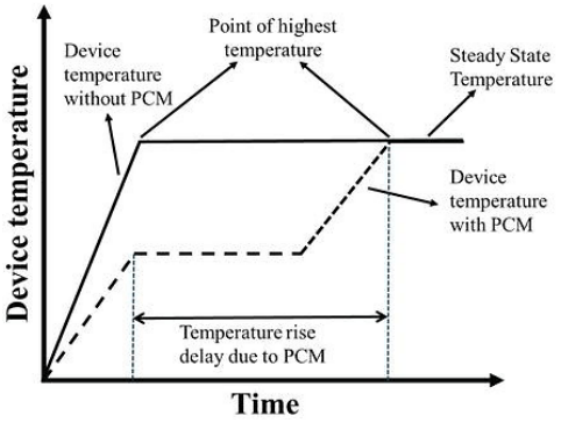


Figure 5. Performance comparison of temperature response of a heat dissipating with and without PCM passive cooling [25]

These results suggest that PCMs might help us cool things down better and come up with ways to manage heat that last. Figure 5 shows how a PCM lowers peak temperatures by about 10 to 15 °C and smooths out temperature changes in a system that gives off heat. This indicates that the system exhibits higher thermal stability and efficiency when used for passive cooling compared to a system without PCM. Figure 6 shows the charging and discharging cycles, which show how PCMs work with free cooling. While charging, the PCM absorbs extra heat and melts it, which stores thermal energy. It then hardens and releases the heat it has stored, which lets it cool down without using any mechanical devices while it is discharging.

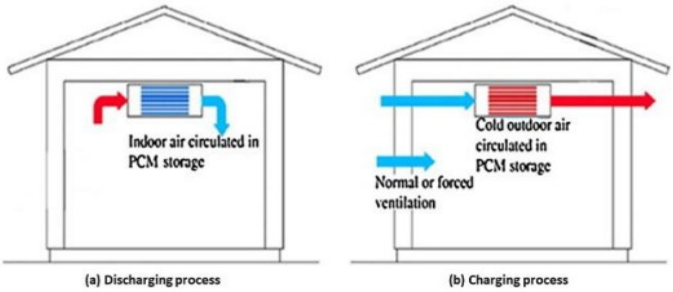


Figure 6. The concept of free cooling PCM method for solar cell systems: (a) PCM charging, (b) PCM discharging [26]

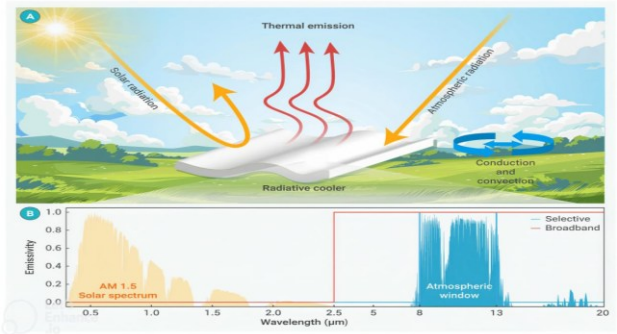
However, PCMs face challenges such as low thermal conductivity, leakage risk, high encapsulation cost, and long-term stability issues.

3.3. Radiative Cooling Techniques

Radiative cooling is a contemporary approach to cool things without consuming power. It radiates heat to space in the mid-infrared atmospheric transparency window (8–13 μm); this is a type of thermal radiation. Photovoltaic modules can cool down to a temperature below the air around them, even when the sun is shining directly on these modules. They do this by using metamaterials or coatings that exclusively reflect sunlight and release higher levels of infrared radiation. New research shows that applying radiative cooling coatings to silicon and perovskite solar cells can lower their operating temperatures by 5 to 10 °C. This makes them last longer and use less power. Businesses still encounter significant challenges with radiative cooling materials because they do not operate optimally on a large scale and don't remain stable in the environment for long [27].

Figure 7 shows the main ideas behind how radiative cooling works. It shows how a surface loses heat through solar absorption, radiation from the atmosphere, thermal emission into space, and convection/conduction. It also analyzes different spectral designs and shows that selective emitters, which reflect ample sunlight and emit a lot of mid-infrared light, are the highly effective for zero-energy cooling.

Figure 8 shows that radiative cooling can be a good way to keep solar cells from getting too hot without using any energy. Figure 8 shows that radiative cooling structures work with photovoltaic modules to let thermal radiation through the atmospheric transparency window while blocking



solar absorption. When this method is used, the solar cell can lose heat to space all the time when it's outside, which makes it much cooler. Radiative cooling makes solar cells work better over time by lowering the amount of energy they lose when the temperature changes, increasing the amount of power they make, and making them more dependable. It does all of this without needing more power or complicated cooling systems.

Figure 7. Basic principles of radiative cooling method for solar cell systems: (a) budgets on a radiative cooler, (b) Spectrum of the ideal selective and broadband cooler [27].

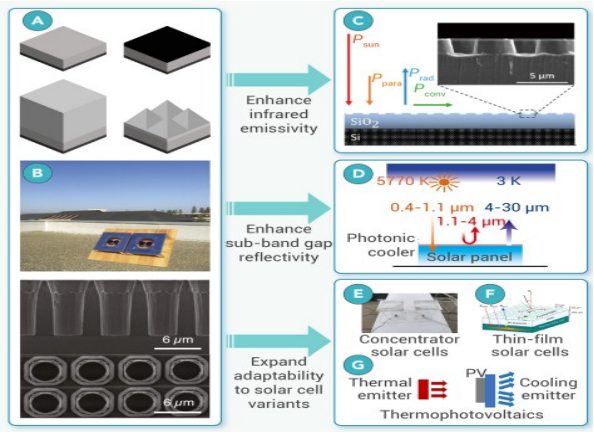


Figure 8. different radiative cooling approaches for solar cells, [27].

Practically, Radiative cooling coatings face scalability and durability challenges, as environmental factors such as dust and surface degradation reduce their efficiency over time. Recent research addresses this by developing self-cleaning surfaces and low-cost polymer paints to ensure long-term stability.

Table 1. Summary of Passive Thermal Mitigation Strategies

Strategies	Temp. Reduction (°C)	Efficiency Gain (%)	Advantages	Limitations	Cost
Heat sinks	~10	~2–3	Simple, passive	Weight, installation	Low–Medium
PCM	8–20	~3–5	Thermal storage	Leakage, low conductivity	Medium
Radiative cooling	5–10	~2–4	Zero energy	Dust, durability	Medium

4. Active Thermal Mitigation Strategies:

Active thermal mitigation technique use cooling systems that don't rely on solar panels to help keep the temperature steady. Active methods can substantially reduce temperatures, but only in a controlled way. They come in handy when the weather is hot and sunny. However, active cooling systems involve high costs and significant maintenance requirements, which may limit their practical use., active cooling is still a good choice if the extra costs for energy and infrastructure are worth the performance gains [28].

4.1. Air and Liquid Cooling

Air or water is often used to cool solar cells. When the air is cooled, convective heat transfer works better because it moves across the module's surface more quickly. Liquid cooling, on the other hand, removes more heat because liquids are better at holding and moving heat. Research indicates that liquid-cooled photovoltaic modules can lower temperatures by 20 to 30 degrees Celsius. This makes the power more reliable. These methods do not operate efficiently under varying conditions, especially large or distant ones. Some of these problems include leaking, getting dirty, requiring excessive pumping power, and needing more maintenance [29].

In 2022 [30], Aditya Rio Prabowo, Prasetyo, Singgih Dwi, and Zainal Arifin investigated the possibility of using nanofluids to increase the efficiency of photovoltaic solar cells in thermal collectors. Active cooling prevents PV/T systems' photovoltaic solar cells from overheating.

Additionally, it allows heat to enter a working fluid that is in motion. The goal of this study was to create a numerical model of a PV/T collector with various riser configurations so that the mass flow rate and working fluid type could be used to observe the system's performance. Heat motion and composition were investigated using ANSYS Fluent and ANSYS Steady State-Thermal. According to the findings', photovoltaic cooling efficiency is increased by 49.8% when a thermal collector is used. Building a rectangular riser and allowing SiO2 nanofluid to flow over it at a speed of 0.01 kg/s proved to be the most efficient way to use electricity. In most cases, changing the fluid and flow rate produced the same outcome.

Figure 9 shows how different working fluids change the PVT system's photovoltaic solar cell's electrical and thermal efficiencies. The results show that nanofluids are better coolants than water because they efficiently transfer heat, which lowers the temperatures at which photovoltaic systems work. The SiO_2 nanofluid was the best of the fluids that were tested. It was about 11.63% efficient at using electricity and about 14.31% efficient at using heat. CuO and ZnO nanofluids are better than water, but not as good as SiO_2. The picture shows that using nanofluids to better control heat makes PV electricity work better. But the differences between working fluid are still not very big.

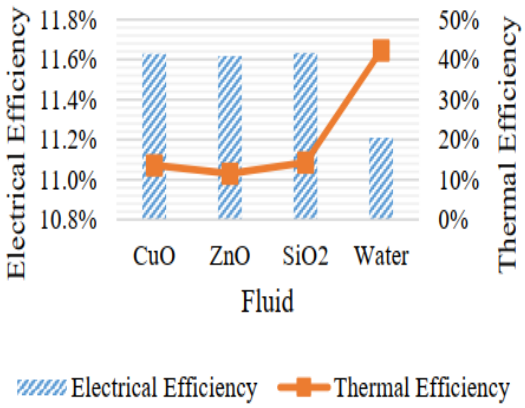


Figure 9. PV solar cell efficiency for different working fluids [30]

Active cooling introduces a parasitic energy penalty, typically ranging from 2–5% for liquid cooling systems and 10–15% for thermoelectric coolers (TECs). Therefore, maintaining a balance between energy consumption and thermal gain is crucial for overall system performance.

4.2. Photovoltaic–Thermal (PV/T) Systems

Photovoltaic-thermal (PV/T) systems use solar cells and thermal collectors to make heat and electricity at the same time. PV/T systems keep the photovoltaic layer from getting too hot. This keeps them from running out of power and allows them to perform optimally. After the heat has been collected, it becomes thermal energy. You can use this energy to warm up homes, businesses, and other places. Because it can do both electrical and thermal work, this device usually uses 60 to 70 percent less energy. When space is limited and energy services need to be combined, PV/T systems are great for building-integrated photovoltaic (BIPV) applications. Planning the system is hard, getting started costs a lot, and there are still big problems with making sure that the electrical and thermal performance are balanced [31]. A key challenge in PV/T systems is the trade-off between electrical and thermal performance; higher fluid temperatures for heating applications often lead to reduced electrical efficiency of the PV cells.

4.3. Thermoelectric Cooling

Thermoelectric cooling sends electricity through modules to cool solar cells. The Peltier effect causes this to happen. This method is great for getting rid of hot spots and some solar applications because it is very small, can perfectly control temperature, and doesn't have any moving parts. Thermoelectric coolers, on the other hand, don't work very well and use a lot of power, and therefore, may not merit further development and deployment efforts. It is only used in small systems or places where the heat can be quickly removed or cooled down. Researchers are still trying to make systems more desirable so that thermoelectric materials work better in general [32].

Table 2. Summary of Active Thermal Mitigation Strategies

Strategies	Temp. Reduction (°C)	Efficiency Gain (%)	Advantages	Limitations	Cost
Air cooling	10–20	Moderate	Simple, easy implementation	Depends on environment	Low
Liquid cooling	20–30	High	Effective heat removal	Leakage, pumping, maintenance	High
PV/T system	Significant	~49.8%	Electrical + thermal output	Complex, expensive	High
Thermoelectric (TEC)	Local cooling	Moderate	Precise, compact	High power consumption	High

5. Conventional Silicon Solar Cells (Crystalline c-Si)

Conventional crystalline silicon (c-Si) solar cells dominate the photovoltaic market, owing to their technological maturity, long operational lifetime and cost-effectiveness. However, their performance is severely affected by the high operating temperatures, particularly under hot and high irradiance conditions. Recent c-Si developments e.g. TOPCon and HJT increase the thermal stability (lower temperature coefficients) while micro-textured surfaces limit the absorption of heat. The efficiency of silicon solar cells drops with temperature (negative temperature coefficient of about -0.4 to -0.5%/°C) due to bandgap narrowing, increased intrinsic carrier concentration and higher recombination rates. Thermal effects result in loss of open-circuit voltage and fill factor and hence dramatic decline in overall power conversion efficiency, as well as increased material degradation and reduced module lifetime [33].

A variety of researchers have looked into different ways to reduce the heat produced by silicon based photovoltaic systems. Phase change materials (PCMs) [34], radiative cooling coatings [35] and evaporative cooling structures [36] are examples of passive cooling techniques that do not require any additional energy to maintain a stable temperature. Experimental studies have demonstrated that PCMs can lower temperatures by several degrees Celsius. Evaporative and radiative cooling methods can lower temperatures in hot climates by more than 15°C, which makes things much more efficient. These passive methods are appealing because they do not have a complex application process nor incur high costs [37].

Active cooling systems like forced air, liquid cooling, and photovoltaic thermal (PV/T) hybrid systems let you control the temperature better and use less energy, but they are significantly more difficult to utilize and need more maintenance [38]. Even with these changes, traditional silicon solar cells still have problems because their bandgap is too narrow and they are too sensitive to temperature compared to newer technologies like III-V and perovskite solar cells. Researchers are still trying to discover how to combine silicon cells with better thermal management systems and long-lasting encapsulation materials to enable them to maintain exceptional performance across both high and low temperature environments.

In 2022 [39], Valiev et al. demonstrated how to fabricate and enhance the performance of single-, double-, and multilayer anti-reflection coatings (ARCs) for silicon solar cells with smooth and rough surfaces. This study examines the effectiveness of these ARCs on crystalline silicon solar cells in terms of light and electricity. The coatings consist of SiO_2, SiN_x, TiO_2, MgF_2, and Al_2O_3. Figure 10 demonstrate that multilayer ARC structures significantly outperform ARCs with one or two layers due to destructive interference. This results in fewer light waves in the visible spectrum (400-700 nm) being reflected by surfaces. Simulations show that uncoated silicon reflects over 30% of incident light. However, optimized single-layer coatings can reduce reflectance to 8%-10%. With two or three layers, reflectance drops to less than 5% over a wider range of wavelengths. Additionally, advanced ARCs can contribute to thermal mitigation by reflecting non-useful near-infrared radiation and enhancing surface emissivity, thereby improving heat dissipation.

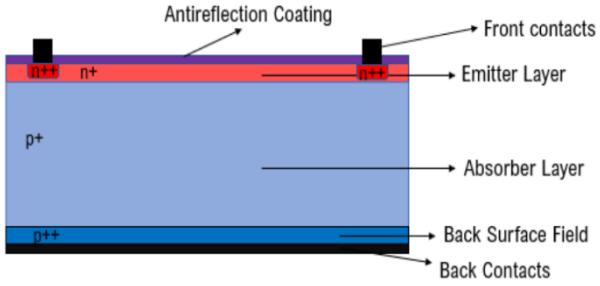


Figure 10. Typical structure of a C-silicon solar cell [39]

6. Thin-Film Solar Cells

Thin-film solar cells have attracted significant attention due to their lightweight characteristic, lack of material requirement, flexibility and mass production capability. These benefits make thin-film technologies good for photovoltaic uses in places where heat is a problem and cost is

important. But it's still a significant challenge to keep the temperature stable and make the power conversion work better. When it comes to thin-film technologies, solar cells made of CdTe and CIGS can handle heat better than regular crystalline silicon cells [40]. CIGS solar cells generally have better tolerance for high temperature operation than CdTe, although CdTe devices typically have lower temperature coefficients (−0.2 to −0.3%/°C) indicating relatively stable performance under thermal variation. Recent research shows that changing the thickness of the absorber layer, buffer layers, and back surface field (BSF) materials can enhance a device's performance and keep it safe from damage caused by temperature changes. Researchers have discovered that this type of structural engineering keeps electrical properties stable even when the temperature rises [41].

Wide-bandgap materials are a good way to make thin-film solar cells less sensitive to heat these days, by limiting thermally generated carriers and reducing the rise of the reverse saturation current, this helps to maintain a more stable open-circuit voltage and a lower temperature coefficient at elevated temperatures.Adding materials like cubic silicon carbide (3C-SiC) and gallium arsenide (GaAs) as secondary or buffer layers can help the device move carriers more easily, lose less energy when carriers recombine, and be less likely to break down when it gets hot. Such properties are attributed to multiple factors, including effective heat conduction and a wide band gap. [42].

The selection of design materials and interfaces is also a critical factor when evaluating a device's efficiency, quality, and lifetime under high-temperature conditions. Recent studies utilizing quantitative data and experimental methodologies demonstrate that the application of thermally stable materials, as opposed to traditional buffer layers, substantially reduces performance degradation at elevated temperatures. Adding metallic nanoparticles to plasmonic nanostructures has also been shown to make them absorb more light and raise the short-circuit current density without changing how stable they are thermally [43].

Overall, recent developments demonstrate that when wide-bandgap materials, optimal layer designs, and sophisticated optical control techniques are employed, thin-film solar cells can be extremely stable and efficient at high temperatures. According to recent studies conducted between 2022 and 2025, these developments make thin-film technology attractive options for next-generation solar systems that can withstand extreme heat and hostile environments. Chauhan, Sweety, Anuj K. Sharma, and Nitin Singh Singha will test how well solar cells work and how stable they are in 2025. To do this, they use thin-film technology made of copper indium gallium selenide (CIGS) [44]. They work on redesigning devices to enable them to be more efficient and making sure they can handle high temperatures. The writers talk about how changing the material's structure, composition, and interface affects how well it can handle heat damage and how well it can convert power. These are important for making sure that things work well in places where it gets very hot a lot of the time, like in real life. The results show that some design choices can make CIGS solar cells more stable without changing how well they work as solar cells. This is because they can help keep things from getting lost when the weather changes. The results show that CIGS is a better way to make thin-film solar panels with long operational lifetimes and superior functionality.
Figure 11 shows that adding a Sb_2S_3 back surface field (BSF) layer to the proposed CIGS thin-film solar cell enables it to perform at higher levels. The device had a fill factor of 80.31%, a short-circuit current density of 42.08 mA/cm^2, and an open-circuit voltage of 1.069 V. This meant that the whole process of changing power only worked 35.94% of the time. These results show that the Sb_2S_3 BSF layer really does help with recombination losses and speed up the flow of charge. This makes the system more stable and lets it work better when the temperature rises.

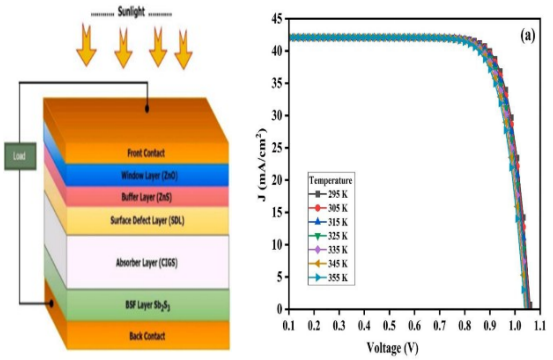


Figure 11. Thin film solar cells design: (a) Proposed structure design, (b) J-V characteristics of the proposed solar cell design with Sb2S3 BSF layer [44].

In 2021, Sobayel, M. K., et al. enhanced the efficiency of Cu (In, Ga) Se_2 composite thin-film solar cells (CIGS) by incorporating a cubic carbon-silicon (3C-SiC) dielectric layer between the conventional dielectric layer and the absorber layer [45]. Theoretical and experimental studies demonstrate that 3C-SiC can enhance carrier transport and reduce losses attributed to irradiation and interface inhomogeneity. Compared to traditional CIGS structures that only use a CdS layer as the dielectric, this makes them more efficient and less likely to break down from heat. A comparative analysis with a reference structure was conducted to evaluate the impact of defect density at the 3C-SiC/CIGS interface and its thermal stability on the overall performance of thin-film solar cells. This showed that using 3C-SiC as a dielectric layer could help these cells work better. Figure 12 shows a diagram and the most important performance metrics for a proposed i-ZnO/3C-SiC/CIGS/Mo thin-film solar cell. The I–V characteristics and spectral response analysis, which were done with 3C-SiC buffer layers of different thicknesses, show that using cubic silicon carbide as a buffer layer enables the device to achieve enhanced photovoltaic performance. The optimized structure has a Voc of 0.94 V, a Jsc of 31.46 mA/cm^2, and an FF of 85.37%, which means it is 25.51% efficient. This shows that 3C-SiC is better and more stable at high temperatures than CdS-based designs because it has a wide bandgap [45].

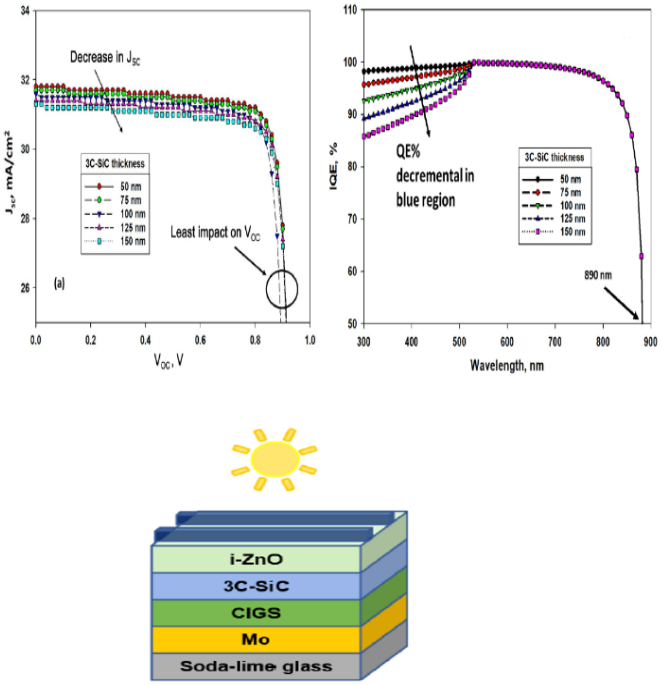


Figure 12. Proposed i-ZnO/3C-SiC/CIGS/Mo thin-film solar cell: (left) The schematic diagram, (a) I–V characteristics, (b) spectral response of the 3C-SiC/CIGS solar cell structure with varied buffer layer thickness of 3C-SiC [45].

In a recent study on weather-adaptive photovoltaic facades, they show the importance of choosing materials that can endure heat and humidity in hot climates. CdTe and CIGS thin-films are known to work well under dry conditions, as they are not affected by temperature and stable in hot environments [46]. These studies further confirmed that randomly ordered silver nanoparticles embedded into the active layer of thin-film silicon solar cells improve the light absorption particularly in the infrared spectrum. The plasmonic enhancement is modeled by the Maxwell-Garnett effective medium theory and the Percus-Yevick correction [47], showing enhancement of the external quantum efficiency and the short-circuit current density. And that makes more electric, in turn.

7. Perovskite solar cells (PSCs) structures and performance analysis

Perovskite solar cells (PSCs) are now more efficient, cheaper, and easier to change the bandgap [48], yet – several adjustments must be made. This is mostly because perovskite materials are not optimal at

high temperatures This instability is mainly attributed to degradation mechanisms such as moisture ingress, ion migration, and phase transitions, which accelerate performance deterioration under elevated temperatures, and lead-based formulations are toxic. This enables them to be less dependable and, in the end, less suitable for business applications [49]. Significant research efforts have produced a range of design approaches to overcome these issues. Some of the best ways to keep things safe in space, where conditions can be very harsh, are to use advanced, airtight packaging to keep out extreme conditions, gradient buffer layers to reduce mechanical stress, and self-healing structures to fix damage from radiation. Poly (2-vinylnaphthalene) (PVN) stops ions from moving in cells that use $FAPbI_3$ when it is added to the PTAA hole-transport layer. This is a great example of how material engineering can make charge-transfer layers better. This change kept more than 80% of the original performance and made the system more than 23% more efficient after 1000 hours of thermal cycling. This means that the thermal stability has improved [50].

In 2025, Thomas, Kevin, and others found a new way to control light in photovoltaic cells (PSCs), which are solar cells that can work on both sides. The silica cover did two things. [51]. The coating is a layer that keeps dust and water out and makes sure that light doesn't reflect off of it. This makes sure that everything goes smoothly when things get tough. The study employed modeling to enhance the design of a bifacial PSC. There were ITO, SiO_2, TiO_2, Perovskite, Copper Oxide, and ITO in it. When light hit the electron transport layer, the device had an open-circuit voltage of 1.35 V, a fill factor of 84.24%, a power conversion efficiency (PCE) of 31.00%, and a short-circuit current density of 29.10 mA/cm^2. When light hit the hole transport layer from the side, the PCE was 22.0%. This meant that the bifocality factor was 72.12%. The extra layer of silica helps it pick up light better and keeps it working for a long time, as the results show. Figure 13 shows how the Voc, Jsc, FF, and efficiency change as the absorber layer gets thicker. Accordingly, selecting the optimal thickness is essential for achieving effective coordination between light absorption and carrier transport. The front side of the bifacial structure (ETL) is 27.9% efficient, and the bifacial factor is 71% [49].

Computational design has shown promise for alternatives that don't use lead. A simulation study utilizing SnO_2 as the electron transport layer (ETL) and $CuSbS_2$ as the hole transport layer (HTL) for a $MASnI_3$-based solar cell predicted an efficiency of 29.47%, with a Voc of 1.0241 V, a Jsc of 33.76 mA/cm^2, and FF of 85.22%. Figure 14 shows the cell structure, energy band diagram and J-V characteristics at different defect levels [52]. Thus, PSCs are an appealing option because of their eco-friendly nature with the retention of high performance. The thickness of the top perovskite layer in tandem configurations needs to be just right to achieve the best current matching. As shown in Figure 15, the efficiency of a perovskite/silicon heterojunction tandem cell was increased from 27.02% to 31.67% when the ($CH_3NH_3PbI_{3-x}Br_x$) layer was changed to 0.161 µm [53]. To make things better we need new materials to move charges. So, we can make things work better by using graphene instead of traditional ETMs such as TiO2. One device architecture achieves 20.95% efficiency [54].

Additive engineering is also a crucial step within the process – for instance, adding a mix of polyethylene oxide and polyethylene glycol to the perovskite layer cut down on defects, made it more heat-resistant, and kept 71% of its original performance after 120 hours at 85°C, with an efficiency of 18.7% [55]. Also, using solvent engineering techniques, like switching out DMF for N-methyl-2-pyrrolidone (NMP) in the precursor solution, has been shown to lower intrinsic defects. This results in an indoor efficiency of 35.99% when lit by LEDs [56].

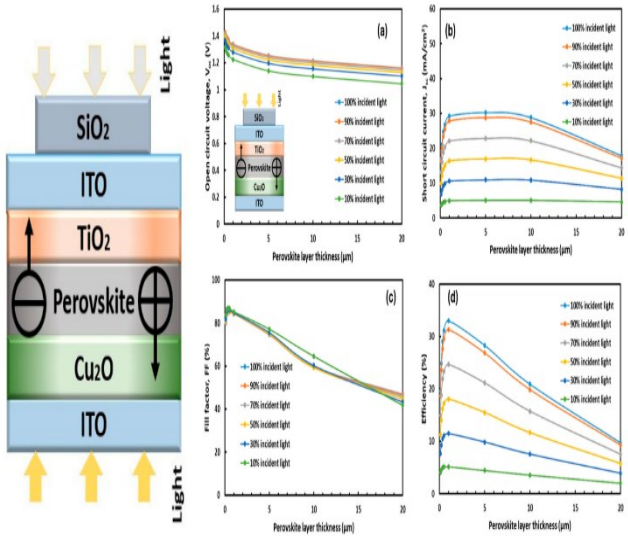


Figure 13. Performance variation in perovskite solar cell for the incident solar spectrum from the HTL side of absorber layer thickness (left) [51]. The variables include: (a) Voc, (b) Jsc, (c) FF, and (d) efficiency.

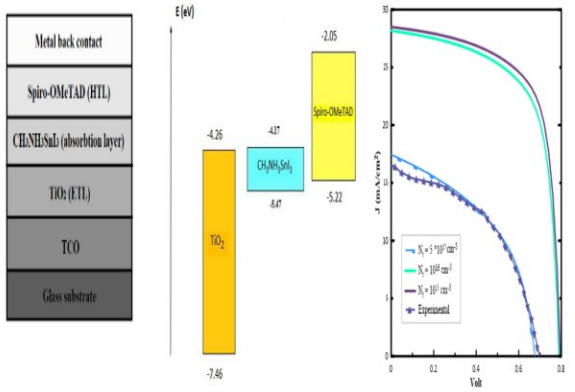


Figure 14. Structural structure of a lead-free perovskite solar cell, Energy band diagram of cell materials and Current-voltage (J–V) curves of the cell under different defect density values [52]

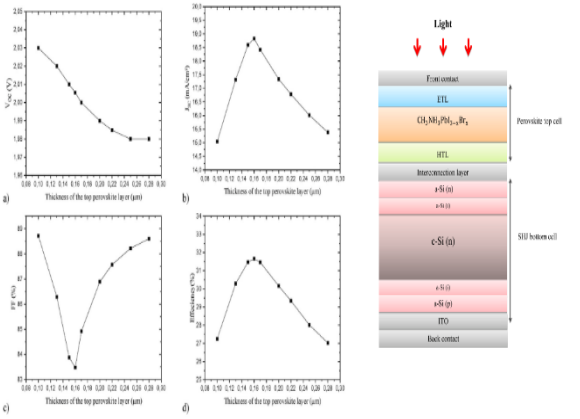


Figure 15. Device structure (left): Influence of the perovskite top-cell thickness on:(a) Voc, (b) Jsc, (c) FF, and (d) efficiency. of the Perovskite/Si tandem device [53].

Perovskite solar cells (PSCs) hold exceptional promise, achieving high laboratory efficiencies comparable to advanced technologies like III-V multi-junction cells, while offering benefits such as tunable bandgaps and simpler, lower-cost manufacturing. Their thermal and photochemical instability remains a key challenge, contributing to a decrease in operational lifespan. This makes them an unpopular choice among businesses. They need a dedicated, multi-faceted research effort that only looks at how to make things more stable in order to get the most out of their business. This means coming up with better ways to finish things, making things that don't have led in them, and improving interfacial engineering [57].

8. High-Temperature Tolerant Solar Cell structures

The first step in making solar cells better is to make single-junction cells better. In other words, you need to pick semiconductor materials that are of high quality and have good bandgaps and other important characteristics. For example, GaAs works well at high temperatures, and InGaN works well at high voltages. Engineers added optical coatings and layers that don't reflect light to make sure the cell could take in as much light as possible.

8.1. Single junction solar cell structures

Conventional silicon cells suffer from a decrease in efficiency with increasing temperature, losing approximately 0.4-0.5% of their efficiency for each degree Celsius increase above room temperature [58]. Therefore, studies have focused on solving this problem. Wang and colleagues presented a study on the thermal effect on the performance of single-junction GaAs cells using monochromatic laser light sources (450, 520, 635 nm) to reduce spectral dispersion and provide a more accurate analysis of loss mechanisms. Simulation results using SCAPS-ID showed that lowering the temperature from 300K to 160K resulted in high PV efficiencies of up to 40% as shown in Fig. 16 [59].

A study was also conducted on a single-junction InGaN solar cell to investigate the effect of indium content and solar radiation intensity on performance. The results demonstrated optimal performance of this cell at 800 K, achieving a power density of 111 mW/cm^2 under concentrated solar illumination (100 suns). Increasing the indium content in the InGaN cell structure further improves performance, making it a suitable option for operation in harsh environments [60]. Zhao et al. confirmed that InGaN solar cells are capable of operating efficiently under extreme thermal conditions, withstanding temperatures exceeding 350-450°C, achieving quantum efficiencies exceeding 80%. The researchers also highlighted the unique properties of InGaN, such as a positive thermal coefficient and a high absorption coefficient, which give it additional advantages for sustainability in harsh conditions as shown in Figure 17 [61]. The results show increased external quantum efficiency, higher current density, and improved J-V characteristics, confirming that nanorod arrays and optical coatings effectively enhance performance compared to bare cells.

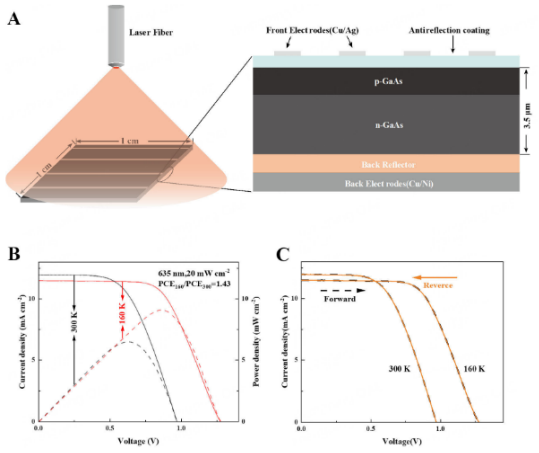


Figure 16. The single-junction GaAs solar cell: (a) Layered schematic circuit (b) Photoelectric conversion efficiency (PCE) and fill factor (FF) change with temperature, (c) The forward-reverse J-V curves at 300/160 K [59].

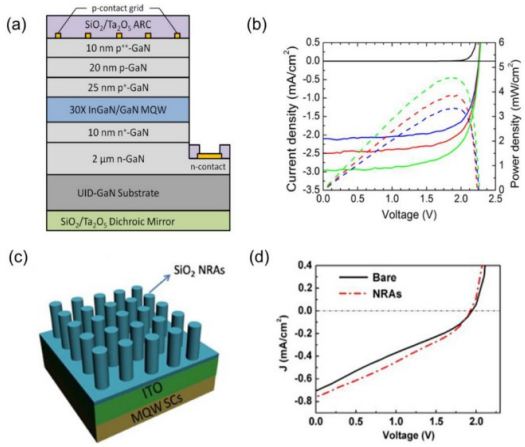


Figure 17. Optical designs for InGaN-based solar cells [61]: (a) schematic with optical coatings, (b) EQE spectra and power density improvement, (c) schematic with antireflective nanorod arrays, and (d) J-V characteristics showing enhanced performance with NRAs compared to conventional cells.

8.2. Multi-stages solar cell structures

Although multi-junction solar cells are highly efficient, surface recombination problems, high manufacturing costs, and poor charge transport remain challenges [62]. Additionally, thermal management in multi-junction cells is more challenging due to non-uniform heat across layers, causing interfacial stress and increased recombination. To address these problems, researchers have conducted several studies in recent years on the development and improvement of multi-junction solar cells to enable them to operate in harsh terrestrial and space environments. Donkata et al studied the integration of ETLs and HTLs into InGaP/InGaAs/Ge multi-junction solar cells. The results showed that the design achieved an efficiency of 49.83%, which is relatively higher than conventional structures as shown in Figure 18 [62].

Labotin and colleagues used III-V materials with a bandgap of 1.4-1.0 eV to design tandem photovoltaic cells, incorporating a high-reflectivity back-reflector (BSR) to recover sub-gap photons toward the emitter. Cells with a bandgap of 1.4/1.2 eV achieved an efficiency of 41.1% at emitter temperature 2400°C, while cells with a bandgap of 1.2/1.0 eV achieved an efficiency of 39.3% at emitter temperature 2127°C, which is consistent with recent efforts to increase efficiency and enhance thermal stability as shown in Figure 19 [63]. Based on the graphical data presented, the study investigates the design and optimization of a two-terminal tandem solar cell featuring a CdTe–$FeSi_2$ heterojunction.

There are many different types of solar cells that have been reported so far. Table 1 shows them all. It tells you what kind of cell it is, what it's made of, how well it changes power, and how stable it can be when the temperature rises. The table shows that GaAs and InGaN, which are single-junction devices with wide bandgaps, can handle high temperatures better than other types of devices. They can handle a lot of abuse and still work well when the temperature is over 700 K. Multi-junction architectures, especially tandem cells made of III-V and CdTe/$FeSi_2$, are better than other types of cells.

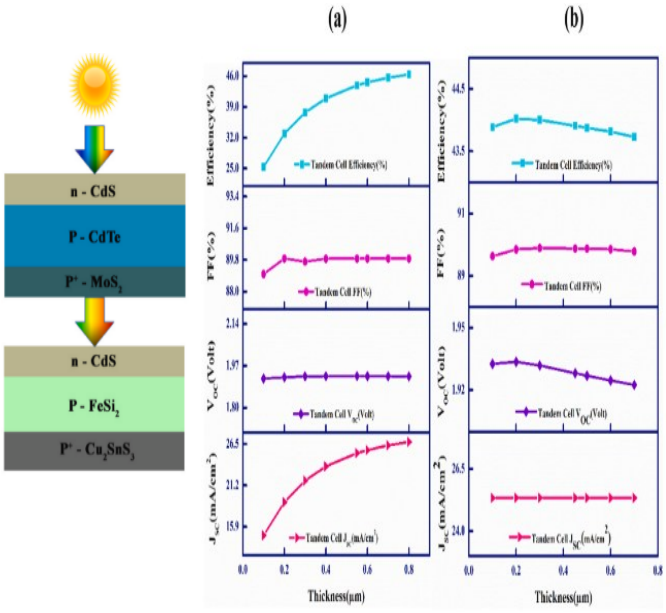


Figure 18. The proposed structure and I-V performance of InGaP/InGaAs/Ge Multi-Junction solar cells [66]

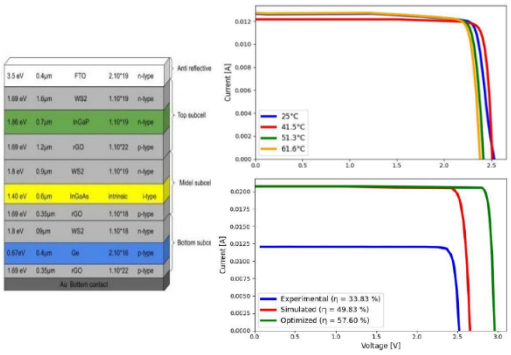


Figure 19. Configuration of the CdTe–FeSi2 2-terminal PV device [67]: (a) Electrical Characteristics (Voc and FF) and (b) Overall Efficiency as a Function of Top-Cell Absorber Thickness.

Conclusion

This review has comprehensively examined recent advances (2017–2026) in thermal effect mitigation strategies for photovoltaic technologies operating under elevated temperature conditions. The analysis confirms that temperature remains a critical factor limiting the efficiency, reliability, and lifetime of solar cells across conventional silicon, thin-film, III–V, and emerging perovskite platforms. Both passive techniques such as heat sinks, phase change materials, and radiative cooling and active approaches including air/liquid cooling, PV/T systems, and thermoelectric cooling demonstrate significant potential for temperature regulation, each with specific advantages and practical trade-offs. Among the reviewed technologies, perovskite and advanced thin-film structures show promising thermal tolerance when supported by proper material and interface engineering. Nevertheless, the absence of fully integrated, cost-effective thermal management solutions remains a key research gap. Future work should focus on experimentally validated hybrid cooling architectures, long-term reliability studies in harsh environments, and scalable designs that balance thermal stability, efficiency, and economic feasibility for next-generation photovoltaic systems.

Acknowledgements

The authors would like to express their sincere gratitude to the departments of both communications and intelligent digital systems engineering and Electrical engineering, college of engineering, university of Mosul, for providing the technical resources and support necessary to carry out this research.

Table 3: Performance comparison of the different thermal effect mitigation strategies for solar cells

Ref. year	Solar cell Structure	Materials / Device Configuration	Efficiency [%]	Therml stability [°K]
[59] 2025	Single junction	GaAs	40	160
[60] 2025	Single junction	PPN InGaN (P-InGaN/P-InGaN/N-InGaN), x = 0.5	26.36	800
[61] 2023	Single junction	InGaN-based solar cell	QE > 80	723
[62] 2023	Single junction	AlGaAs (Window) / p-InGaP / n-InGaP / AlGaInP (BSF)	32.09	-
[63] 2025	Multi-junction	FTO/WS2/InGaP/rGO/WS2/InGaAs/rGO/WS2/Ge/rGO/Au	49.83	298
[64] 2022	Multi-junction (1.2/1.0 ev)	GaInAs/GaInp/AlGaInAs/GaAsSb/ GaInAs/Au	39.3	2400.15
[65] 2023	Multi-junction	GaInP/GaAs/InGaAs	33.88	358
[71] 2024	Multi-junction	GaInP / GaInAs / Ge	35	298
[43] 2025	Thin-film	ZnO/ZnS/SDL/CIGS/ Sb2S3	35.94	360
[45] 2021	Thin-film	i-ZnO/3C-SiC/CIGS/Mo	25.51	-
[47] 2017	Thin-film	ITO/Si(with Ag nanoparticles)/Metale contact	-	-
[66] 2022	Thin-film	Cu/FTO/In2S3/CdTe/FeSi2/Ni	27.35	300
[67] 2024	Thin-film	ZnO/CdS/CIGS/GaAs/Ir	53.2	800
[18] 2025	Perovskite	FTO/ZnO/MASnI3/NiOx/Au	21	290
[49] 2024	Perovskite	ITO/TiO2/Perovskite/Cu2O/ITO	27.9/9.86	400
[50] 2024	Perovskite	ITO / PTAA: PVN / $FAPbI_3$ / C_{60} / BCP / Cu	23	358
[51] 2025	Perovskite	SiO2/ITO/TiO2/ Perovskite /copper oxide/ITO	31	400
[52] 2023	Perovskite	TCO/SnO2/CH3NH3SNi3 /CuSbS2	29.47	-

[53] 2022	Tandem (perovskite)	TiO2/ CH3NH3PbI3− xBrx/Spiro-OMeTAD (top cell)/ a-Si (n) /a-Si (i) / c-Si (n)/ a-Si (i)/ a-Si (p)/ITO (bottom cell)	31.67	-
[54] 2020	Perovskite	glass/ITO/Graphene/CH3NH3PbI3/Spiro-OMeTAD/ Au	20.95	-
[55] 2023	Perovskite	PTAA / $MAPbI_3$ (withPEO+PEG additive) / C_{60} / BCP / Ag	18.7	358
[56] 2024	Perovskite	Glass / ITO / SnO_2 / $(FAPbI_3)_{0.85}(MAPbBr_3)_{0.15}$ / Spiro-OMeTAD / Au (or Ag)	35.99	—
[68] 2024	Perovskite	FTO/ITO / NiOx / $CH_3NH_3PbI_3$ / ZnO / Ag–Al	18	---
[69] 2024	Silicon	PCM (beeswax / paraffin)	14	317
[70] 2021	Silicon	Passive cooling (burlap cloth)	14.75	328.95

References

[1] A. Ashraf and M. Sagheer, "Renewable energy capacity and technological innovations: A review of global trends and future directions," *Environ. Prog. Sustain. Energy*, vol. 44, no. 6, p. e70071, Nov. 2025, doi: 10.1002/ep.70071.

[2] M. Maka and J. Alabid, "Solar energy technology and its roles in sustainable development," *Clean Energy*, vol. 6, no. 3, pp. 476–483, Jun. 2022, doi: 10.1093/ce/zkac023.

[3] S. Guo, H. Xiong, G. Xin, and Y. Shan, "Solar photovoltaics: Silicon cell principles, technology implementation, and future development," in *Proc. 3rd Int. Conf. Materials Chemistry and Environmental Engineering (CONF-MCEE)*, 2023, vol. 7, pp. 778–786, doi: 10.54254/2755-2721/7/20230488.

[4] A. Mdallal, A. Yasin, M. Mahmoud, M. A. Abdelkareem, A. H. Alami, and A. G. Olabi, "A comprehensive review on solar photovoltaics: Navigating generational shifts, innovations, and sustainability," *Sustain. Horizons*, vol. 13, Art. no. 100137, 2025, doi: 10.1016/j.horiz.2025.100137.

[5] A. S. Al-Ezzi and M. N. M. Ansari, "Photovoltaic solar cells: A review," *Appl. Syst. Innov*., vol. 5, no. 4, p. 67, Jul. 2022, doi: 10.3390/asi5040067.

[6] A. Alkuhayli and A. Telba, "Effect of High Temperature on the Efficiency of Grid-Connected PV System," in *Proc. World Congr. Eng. (WCE)*, London, U.K., 2021, pp. 152–156.

[7] L. M. Shaker et al., "Examining the influence of thermal effects on solar cells: A comprehensive review," *Sustain. Energy Res*., vol. 11, Art. no. 6, 2024, doi: 10.1186/s40807-024-00100-8.

[8] A. O. M. Maka and T. S. O'Donovan, "Effect of thermal load on performance parameters of solar concentrating photovoltaic: High-efficiency solar cells," *Energy Built Environ*., vol. 3, no. 2, pp. 201–209, May 2022, doi: 10.1016/j.enbenv.2021.02.002.

[9] A. Ait Ali, M. El Mansouri, A. El Ghzizal, M. Elamrani, and A. El Khamlichi, "The impact of desert regions on solar energy production with the evaluation of groundwater for maintenance: A case study in Morocco," *Sustainability*, vol. 16, no. 13, p. 5476, Jul. 2024, doi: 10.3390/su16135476.

[10] M. Maoz, Z. Abbas, S. A. B. Shah, and V. Lughi, "Recent advances in flexible solar cells: Materials, fabrication, and commercialization," *Sustainability*, vol. 17, no. 5, p. 1820, Feb. 2025, doi: 10.3390/su17051820.

[11] L. A. September, N. Kheswa, N. S. Seroka, and L. Khotseng, "Advanced Developments in Fabrication Techniques and Bandgap Engineering in Perovskite Solar Cells (PSC)," *in Innovations in Perovskite Solar Cell Materials and Devices - Cutting-Edge Research and Practical Applications*, London, UK: IntechOpen, 2025, pp. 1-22, doi: 10.5772/intechopen.1006976.

[12] M. Subhan and A. Abdel-Hamid, "Plasmonic metal nanostructures as performance enhancers in emerging solar cells: A review," *Next Mater*., vol. 6, p. 100509, 2025, doi: 10.1016/j.nxmate.2025.100509.

[13] K. Lakai, S. C. Fong, J. Kassiram, H. C. Swart, and V. Kumar, "Photon management for next generation solar cells," *in Advanced Materials and Technologies for Photovoltaics, Elsevier, Amsterdam, Netherlands*, 2026, ch. 14, pp. 415–434.

[14] N. T. Dintcheva, E. Morici, and C. Colletti, "Encapsulant materials and their adoption in photovoltaic modules: A brief review," *Sustainability*, vol. 15, no. 12, p. 9453, Jun. 2023, doi: 10.3390/su15129453.

[15] R. K. Ratnesh et al., "Recent advances in solar cell technology: Addressing technological challenges, scenarios, and environmental implications in the development of sustainable energy solutions," *New J. Chem*., 2025, doi: 10.1039/D5NJ01234A.

[16] L. Gao, X. Zhang, and W. Hua, "Recent progress in photovoltaic thermal phase change material technology: A review," *J. Energy Storage*, vol. 65, p. 107317, 2023, doi: 10.1016/j.est.2023.107317.

[17] A. D. Dhass, E. Natarajan, and P. Lakshmi, "An investigation of temperature effects on solar photovoltaic cells and modules," *Int. J. Eng. Trans. B: Appl*., vol. 27, no. 11, pp. 1713–1722, Nov. 2014.

[18] A. Mortadi et al., "Investigating temperature effects on perovskite solar cell performance via SCAPS-1D and impedance spectroscopy," *Cleaner Eng. Technol*., vol. 24, p. 100876, 2025, doi: 10.1016/j.clet.2025.100876.

[19] M. K. Hassan, I. M. Alqurashi, A. E. Salama, and A. F. Mohamed, "Investigation the performance of PV solar cells in extremely hot environments," *J. Umm Al-Qura Univ. Eng. Archit*., vol. 13, no. 1, pp. 18–26, 2022, doi: 10.1007/s43995-022-00005-x.

[20] A. Sebastian, K. M. Sajith, M. Das, and S. A. K, "Unveiling the interplay of thickness, band gap and temperature in CIGS solar cells*," London J. Res. Sci.: Nat. Formal*, vol. 25, no. 8, 2025.

[21] I. O. Harmailil, S. M. Sultan, C. P. Tso, A. Fudholi, M. Mohammad, and A. Ibrahim, "A review on recent photovoltaic module cooling techniques: Types and assessment methods," *Results Eng*., vol. 22, p. 102225, Feb. 2024, doi: 10.1016/j.rineng.2024.102225.

[22] A. A. Jasim, A. Fazlizan, M. A. Alghoul, K. Sopian, M. H. Yazdi, and M. A. M. A. Al-Waeli, "Enhancing PV module performance through a novel fin heat sink design: A numerical and experimental study," *Case Stud. Therm. Eng*., vol. 74, p. 106842, Jul. 2025, doi: 10.1016/j.csite.2025.106842.

[23] Z. Arifin, S. Suyitno, D. D. D. P. Tjahjana, W. E. Juwana, M. R. A. Putra, and A. R. Prabowo, "The effect of heat sink properties on solar cell cooling systems," *Appl. Sci*., vol. 10, no. 21, p. 7919, Nov. 2020, doi: 10.3390/app10217919.

[24] S. Kumar and D. Banerjee, "A review on phase change materials for sustainability applications by leveraging machine learning," *in Energy Consumption, Conversion, Storage, and Efficiency, IntechOpen*, 2024, doi: 10.5772/intechopen.114380.

[25] H. J. Akeiber, "Phase change materials in cooling systems: A sustainable approach to thermal management," *Al-Rafidain J. Eng. Sci*., vol. 3, no. 1, pp. 503–529, 2025, doi: 10.61268/4jmhc658.

[26] U. Masood, M. Haggag, A. Hassan, and M. Laghari, "A review of phase change materials as a heat storage medium for cooling applications in the built environment," *Buildings*, vol. 13, no. 7, p. 1595, Jul. 2023, doi: 10.3390/buildings13071595.

[27] H. Chen, X. Liu, J. Liu, F. Wang, and C. Wang, "Radiative cooling applications toward enhanced energy efficiency: System designs, achievements, and perspectives," *Innovation*, vol. 6, no. 10, p. 100999, Oct. 2025, doi: 10.1016/j.xinn.2025.100999.

[28] A. M. Al Sadoon, M. S. Kassim, and R. A. Mahmood, "A comparative study of cooling techniques for photovoltaic panels: Active cooling techniques, a review," *J. Eng. Sustain. Dev*., vol. 28, no. 5, pp. 580–592, Sep. 2024, doi: 10.31272/jeasd.28.5.3.

[29] I. O. Harmailil, S. M. Sultan, C. P. Tso, A. Fudholi, M. Mohammad, and A. Ibrahim, "A review on recent photovoltaic module cooling techniques: Types and assessment methods," *Results Eng*., vol. 22, p. 102225, May 2024, doi: 10.1016/j.rineng.2024.102225.

[30] S. D. Prasetyo, A. R. Prabowo, and Z. Arifin, "Investigation of thermal collector nanofluids to increase the efficiency of photovoltaic solar cells," *Int. J. Heat Technol*., vol. 40, no. 2, pp. 415–422, Apr. 2022, doi: 10.18280/ijht.400208.

[31] S. Hosouli et al., "Photovoltaic-thermal (PVT) solar collector and system overview," *Energies*, vol. 18, no. 21, p. 5643, 2025, doi: 10.3390/en18215643.

[32] I. Karaaslan and T. Menlik, "Numerical study of a photovoltaic thermal (PV/T) system using mono and hybrid nanofluid," *Sol. Energy*, vol. 224, pp. 1260–1270, Aug. 2021, doi: 10.1016/j.solener.2021.06.072.

[33] J. Kang, C. Lee, H. Chung, and P. Bermel, "Design strategies, manufacturing, and applications of radiative cooling technologies," *Nanophotonics*, vol. 14, no. 14, pp. 2355–2395, 2025, doi: 10.1515/nanoph-2025-0159.

[34] S. W. Glunz, R. Preu, and D. Biro, "Crystalline silicon solar cells: State-of-the-art and future developments," *in Comprehensive Renewable Energy*, vol. 1, pp. 353–387, 2012, doi: 10.1016/B978-0-08-087872-0.00117-7.

[35] A. Alshammari, E. Almatrafi, and M. Rady, "Radiative coatings for solar cell cooling: Materials, and applications," *Sol. Energy*, vol. 273, p. 112545, May 2024, doi: 10.1016/j.solener.2024.112545.

[36] I. A. Hasan, I. S. Kareem, and D. A. Attar, "Effect of evaporative cooling combined with heat sink on PV module performance," *J. Univ. Babylon Eng. Sci*., vol. 27, no. 2, pp. 252–264, 2019.

[37] H. A. Nasef, S. A. Nada, and H. Hassan, "Integrative passive and active cooling system using PCM and nanofluid for thermal regulation of concentrated photovoltaic solar cells," *Energy Convers. Manag*., vol. 199, p. 112065, 2019, doi: 10.1016/j.enconman.2019.112065.

[38] S. D. Prasetyo, A. R. Prabowo, and Z. Arifin, "The use of a hybrid photovoltaic/thermal (PV/T) collector system as a sustainable energy-harvest instrument in urban technology," *Heliyon*, vol. 9, no. 2, p. e13390, Feb. 2023, doi: 10.1016/j.heliyon.2023.e13390.

[39] M. Valiei, P. M. Shaibani, H. Abdizadeh, M. Kolahdouz, E. A. Soleimani, and J. Poursafar, "Design and optimization of single, double and multilayer anti-reflection coatings on planar and textured surface of silicon solar cells," *Mater. Today Commun*., vol. 32, p. 104144, Aug. 2022, doi: 10.1016/j.mtcomm.2022.104144.

[40] A. R. Smith, B. Author, C. Author, and D. Author, "Thin-film technologies for sustainable building-integrated photovoltaics," *Energies*, vol. 17, no. 24, p. 6363, Dec. 2024, doi: 10.3390/en17246363.

[41] W. Henni, M. Benyahia, A. Boukortt, and A. Mellit, "Effect of adding Cu_2O as a back surface field layer on the performance of copper manganese tin sulfide solar cells," *Sustainability*, vol. 15, no. 19, p. 14322, Oct. 2023, doi: 10.3390/su151914322.

[42] A. E. Kaloyeros and B. Arkles, "Silicon carbide thin films: Innovations in property, process, and applications," *in Silicon Carbide – Materials, Devices and Emerging Applications*, IntechOpen, 2025, doi: 10.5772/intechopen.1008414.

[43] M. Asif, S. Husain, S. Rehman, T. Hussain, and R. Mohd, "Experimental studies on selected thermal interface materials," *Thermal Science*, vol. 28, no. 4, pp. 2857–2866, 2024, doi: 10.2298/TSCI230911284A.

[44] S. Chauhan, A. K. Sharma, and N. S. Singha, "On the performance and thermal stability of solar cell based on CIGS–Sb_2S_3 combination with >35% power conversion efficiency," *Solid State Commun*., vol. 395, p. 115736, Jan. 2025, doi: 10.1016/j.ssc.2024.115736.

[45] M. K. Sobayel, et al., "Efficiency enhancement of CIGS solar cell by cubic silicon carbide as prospective buffer layer," *Sol. Energy*, vol. 224, pp. 271–278, Aug. 2021, doi: 10.1016/j.solener.2021.05.093.

[46] X. Wu, Y. Zhang, L. Chen, H. Li, and Z. Wang, "Climate-responsive design of photovoltaic façades in hot climates: Materials, technologies, and implementation strategies," *Buildings*, vol. 15, no. 10, p. 1648, Oct. 2025, doi: 10.3390/buildings15101648.

[47] M. Piralaee, A. Asgari, and V. Siahpoush, "Modeling and optimizing the performance of plasmonic solar cells using effective medium theory," *Phys. Lett. A*, vol. 381, no. 5, pp. 489–493, Feb. 2017, doi: 10.1016/j.physleta.2016.11.029.

[48] D. Yun, Y. Cho, H. Shin, and G.-H. Kim, "Development of high-efficiency and high-stability perovskite solar cells with space environmental resistance," *Energies*, vol. 18, no. 13, p. 3378, Jun. 2025, doi: 10.3390/en18133378.

[49] M. I. Hossain, P. Chelvanathan, A. Khandakar, K. Thomas, A. Rahman, and S. Mansour, "Enhanced efficiency of bifacial perovskite solar cells using computational study," *Sci. Rep*., vol. 14, no. 1, p. 12984, Jun. 2024, doi: 10.1038/s41598-024-62487-0.

[50] Y. Shi, et al., "Improving thermal stability of perovskite solar cells by suppressing ion migration," *Small Struct*., vol. 5, no. 10, p. 2400132, May 2024, doi: 10.1002/sstr.202400132.

[51] K. Thomas, M. I. Hossain, P. Chelvanathan, A. Khandakar, A. Rahman, and S. Mansour, "Optimizing light management in bifacial perovskite solar cells using silica-based anti-dust and anti-reflection coatings for harsh environments," *Processes*, vol. 13, no. 2, p. 578, Feb. 2025, doi: 10.3390/pr13020578.

[52] O. Mostafa, N. A. Zidan, W. Abbas, H. H. Issa, N. Gamal, and M. Fedawy, "Design and performance optimization of lead-free perovskite solar cells with enhanced efficiency," *Math. Model. Eng. Probl*., vol. 10, no. 4, pp. 1401–1408, Aug. 2023, doi: 10.18280/mmep.100424.

[53] M. Bacha, A. Saadoune, and I. Youcef, "Design and numerical investigation of perovskite/silicon tandem solar cell," *Opt. Mater*., vol. 131, p. 112671, Sep. 2022, doi: 10.1016/j.optmat.2022.112671.

[54] A. Daraie and A. Fattah, "Performance improvement of perovskite heterojunction solar cell using graphene," *Opt. Mater*., vol. 109, p. 110254, Nov. 2020, doi: 10.1016/j.optmat.2020.110254.

[55] Z. Uddin, M. T. Rahman, M. A. Hossain, M. R. Islam, and M. A. Matin, "Improving thermal stability of perovskite solar cells by thermoplastic additive engineering," *Energies*, vol. 16, no. 9, p. 3621, May 2023, doi: 10.3390/en16093621.

[56] E. Q. Han, et al., "High-performance indoor perovskite solar cells by self-suppression of intrinsic defects via a facile solvent-engineering strategy," *Small*, vol. 20, no. 4, p. 2305192, Jan. 2024, doi: 10.1002/smll.202305192.

[57] P. Kumari, S. Prasanthkumar, and L. Giribabu, "Recent progress on perovskite based indoor photovoltaics: Challenges and commercialization," *Sol. Energy*, vol. 284, p. 113049, 2024, doi: 10.1016/j.solener.2024.113049.

[58] C. Sun, Y. Zou, C. Qin, B. Zhang, and X. Wu, "Temperature effect of photovoltaic cells: a review," *Adv. Compos. Hybrid Mater*., vol. 5, no. 4, pp. 2675–2699, 2022, doi: 10.1007/s42114-022-00533-z.

[59] S. Wang, et al., "Achieving ~40% power conversion efficiency increase of single-junction GaAs solar cells via temperature regulation," *Energy Mater*., vol. 5, pp. 500095, 2025, doi: 10.20517/energymater.2024.303.

[60] H. U. Manzoor, N. S. Shiong, M. N. Manzoor, and T. Manzoor, "Enhancing InGaN solar cell performance under concentrated sunlight: A SCAPS-1D simulation approach," *Nano Select*, vol. 6, no. 11, p. e70018, Apr. 2025, doi: 10.1002/nano.70018.

[61] Y. Zhao, et al., "Toward high efficiency at high temperatures: Recent progress and prospects on InGaN-based solar cells," *Mater. Today Energy*, vol. 31, p. 101229, Jan. 2023, doi: 10.1016/j.mtener.2022.101229.

[62] A. A. Saif, "Modelling and efficiency optimisation of single-junction InGaP solar cells," *J. Eng. Sci. Technol*., vol. 19, no. 6, pp. 2191–2206, Dec. 2024.

[63] K. A. Donkata, D. T. Cotfas, P. A. Cotfas, K. Beltako, and M. M. Dzagli, "InGaP/InGaAs/Ge multi-junction solar cells efficiency improvements using interposed transport layers," *Sol. Energy Sustain. Dev*., vol. 14, no. 1, pp. 316–333, Apr. 2025, doi: 10.51646/jsesd.v14i1.338.

[64] A. LaPotin, et al., "Thermophotovoltaic efficiency of 40%," *Nature*, vol. 604, no. 7905, pp. 287–291, Apr. 2022, doi: 10.1038/s41586-022-04473-y.

[65] X. Wu et al., "Accelerated aging of unencapsulated flexible GaInP/GaAs/InGaAs solar cells by means of damp heat and thermal cycling tests," *Heliyon*, vol. 9, no. 6, p. e16462, Jun. 2023, doi: 10.1016/j.heliyon.2023.e16462.

[66] M. F. Rahman et al., "Design and numerical investigation of cadmium telluride (CdTe) and iron silicide ($FeSi_2$) based double absorber solar cells to enhance power conversion efficiency," *AIP Adv*., vol. 12, no. 10, p. 105101, 2022, doi: 10.1063/5.0108459.

[67] H. U. Manzoor, T. Manzoor, S. Hussain, M. N. Manzoor, and A. Zoha, "Swarm-Optimized ZnO/CdS/CIGS/GaAs Solar Cell for Enhanced Efficiency and Thermal Resilience," *Adv. Energy Sustain. Res*., vol. 5, Art. no. 2400203, 2024, doi: 10.1002/aesr.202400203.

[68] A. Mortadi, E. El Hafidi, M. Monkade, and R. El Moznine, "Investigating the influence of absorber layer thickness on the performance of perovskite solar cells: A combined simulation and impedance spectroscopy study," *Mater. Sci. Energy Technol.*, vol. 7, no. July 2023, pp. 158–165, 2024, doi: 10.1016/j.mset.2023.10.001.

[69] M. A. Mohammed, B. M. Ali, K. F. Yassin, O. M. Ali, and O. R. Alomar, "Comparative study of different phase change materials on the thermal performance of photovoltaic cells in Iraq's climate conditions," *Energy Rep*., vol. 11, pp. 18–27, Nov. 2024, doi: 10.1016/j.egyr.2023.11.022.

[70] M. Dida, S. Boughali, D. Bechki, and H. Bouguettaia, "Experimental investigation of a passive cooling system for photovoltaic modules efficiency improvement in hot and arid regions," *Energy Convers. Manag*., vol. 243, pp. 114328, Sep. 2021, doi: 10.1016/j.enconman.2021.114328.

[71] L. M. Nieto Nieto, J. P. Ferrer Rodríguez, R. M. Campos, and P. J. Pérez Higueras, "Multi-junction solar cell measurements at ultra-high irradiances for different temperatures and spectra," *Sol. Energy Mater. Sol. Cells*, vol. 266, pp. 112651, Nov. 2024, doi: 10.1016/j.solmat.2023.112651.