REVIEW

Examining the influence of thermal effects on solar cells: a comprehensive review



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Abstract

Solar energy has emerged as a pivotal player in the transition towards sustainable and renewable power sources. However, the efficiency and longevity of solar cells, the cornerstone of harnessing this abundant energy source, are intrinsically linked to their operating temperatures. This comprehensive review delves into the intricate relationship between thermal effects and solar cell performance, elucidating the critical role that temperature plays in the overall efficacy of photovoltaic systems. The primary objective of this review is to provide a comprehensive examination of how temperature influences solar cells, with a focus on its impact on efficiency, voltage, current output, and overall stability. By synthesizing existing knowledge and exploring recent advances in the field, we aim to elucidate the underlying mechanisms of thermal effects and offer insights into mitigating their adverse consequences. Our review encompasses a thorough discussion of the fundamentals of solar cells, including their operation and various types, before delving into the intricacies of thermal effects. We present an overview of experimental techniques for thermal analysis, factors influencing temperature variations, and strategies to alleviate thermal stresses. Additionally, we offer real-world case studies and discuss future trends and research directions, providing a comprehensive roadmap for advancing solar cell technology. In an era where the harnessing of solar energy has become increasingly vital, understanding and addressing thermal effects are imperative to maximize the efficiency and longevity of solar cells. This review article serves as a valuable resource for researchers, engineers, and policymakers by shedding light on the significance of thermal effects on solar cell performance and guiding the pursuit of innovative solutions in the quest for more efficient and sustainable photovoltaic systems.

Keywords Renewable energy, Photovoltaic cells, Solar cell efficiency, Thermal effects, Sustainable energy

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Introduction

In an era of accelerating climate change and environmental challenges, the quest for sustainable and renewable energy sources has become paramount. Among the myriad alternatives, solar energy stands out as one of the most promising solutions to mitigate the world's growing energy demands while curbing greenhouse gas emissions (Kuşkaya et al., 2023). In this comprehensive review, we embark on a journey to explore a crucial facet of solar energy harnessing-the influence of thermal effects on solar cell performance. Through a detailed analysis of thermal effects and their impact on solar cell efficiency, voltage, and current output, we aim to shed light on a critical yet often overlooked aspect of photovoltaic technology. Solar energy has ascended to the forefront of the global energy landscape due to its abundance, accessibility, and sustainability. It represents a beacon of hope in a world grappling with the challenges posed by finite fossil fuel reserves and the environmental consequences of their combustion. The inexhaustible supply of sunlight offers a tantalizing solution to our energy needs, harnessing a clean, renewable resource that can reduce our dependence on fossil fuels and combat climate change (Akaev & Davydova, 2023). The transition to solar energy holds immense promise, not only for meeting our growing energy demands but also for reducing greenhouse gas emissions and minimizing the environmental impact of energy production. Solar power installations can be deployed at various scales, from residential rooftops to massive utility-scale solar farms, making it a versatile and scalable energy source that can be tailored to the needs of different regions and communities (Chanchangi et al., 2023).

At the heart of solar energy conversion lies the solar cell, a semiconductor device that transforms sunlight into electricity. The efficiency of these cells is a critical parameter that determines how effectively they can convert incoming sunlight into electrical power. Solar cell efficiency is defined as the ratio of the electrical energy output to the incoming solar energy input and is typically expressed as a percentage (Mohammad & Mahjabeen, 2023a). Efficiency is the lifeblood of solar cell technology, as it directly impacts the cost-effectiveness of solar energy generation. High-efficiency solar cells can convert a larger portion of sunlight into electricity, reducing the number of cells and surface area required to generate a given amount of power. This, in turn, leads to lower installation and maintenance costs, making solar energy more accessible and economically viable (Bilal & Andajani, 2023). Understanding and mitigating thermal effects on solar cells is crucial for advancing the efficiency and reliability of solar energy systems. Solar cells, as the fundamental components of photovoltaic technology,

exhibit intricate connections to temperature variations, significantly impacting their performance (Additional files 1, 2, 3, 4).

The efficiency of solar cells, a pivotal parameter in converting sunlight into electrical energy, is intricately linked to temperature. As temperatures rise, electronhole recombination rates within the solar cell increase. This temperature-induced acceleration, governed by the Arrhenius equation, leads to decreased efficiency. Elevated temperatures alter the dynamics of charge carriers, hindering their contribution to electrical current generation. The relationship between temperature and efficiency underscores the need for a nuanced examination to optimize solar cell performance. Temperature variations influence the bandgap properties of materials within solar cells (Asif, et al., 2023). Bandgap, representing the energy difference between valence and conduction bands, plays a crucial role in photon absorption. At higher temperatures, the bandgap of semiconductor materials can shift, impacting the range of photons they can absorb. Materials with smaller bandgaps may absorb lower-energy photons but may also be more susceptible to thermal losses. Understanding these alterations is essential for selecting materials that maintain optimal performance across diverse environmental conditions. Solar cells operate in diverse environments, from extreme heat in deserts to sub-zero temperatures in colder climates. Recognizing the impact of these conditions on solar cell performance is crucial for optimizing efficiency. Extreme temperatures introduce thermal stress, affecting overall stability and functionality. Therefore, a nuanced examination of thermal effects under different environmental conditions is essential for developing robust and reliable solar energy systems. In essence, the significance lies in the direct correlation between temperature variations and reduced efficiency. This knowledge is fundamental for researchers, engineers, and policymakers aiming to enhance solar energy systems' performance and overcome challenges posed by diverse environmental conditions (Bhore et al., 2023).

Exploring the current landscape of thermal effects on solar cells requires a comprehensive understanding of existing literature. This section provides an overview of recent studies, emphasizing the unique contributions of this review to the evolving field. While previous reviews have covered a broad spectrum of topics, ranging from experimental techniques to internal and external factors influencing solar cell performance, a discernible gap remains in synthesizing the latest advancements. In contrast to many existing reviews offering general overviews, this comprehensive review concentrates on recent developments, conducting a meticulous analysis of the most recent studies. The focused lens on the latest research findings distinguishes this review, ensuring an up-to-date and comprehensive analysis reflective of cutting-edge developments (Mohammad & Mahjabeen, 2023b). This approach allows for a deeper exploration of the nuances associated with thermal effects on solar cells, contributing to a more detailed understanding of the subject matter. One unique aspect lies in the commitment to a meticulous analysis of the latest research findings. While other reviews may touch upon recent studies, this review goes further, critically examining and synthesizing these findings (Gerarden, 2023). The goal is to move beyond surface-level discussions and provide readers with insights into the methodological approaches, results, and implications of recent research. This commitment to a detailed analysis distinguishes this review as a valuable resource for researchers, practitioners, and stakeholders in the field of solar energy (Ye et al., 2023). To enhance the clarity of literature summarization, providing quantitative values for context becomes imperative. For instance, discussions on solar cell efficiency should include typical efficiency ranges to offer readers a more concrete understanding. By incorporating specific examples and findings, this section transitions from generic descriptions to a more data-driven and informative analysis. This approach not only strengthens the credibility of the review but also ensures that readers gain a more tangible grasp of the discussed concepts and their practical implications (Mohammad & Mahjabeen, 2023a).

In exploring the existing landscape of thermal effects on solar cells, this literature review synthesizes insights from eight key articles, each contributing to the understanding of the nuances and challenges associated with thermal influences on solar cell performance. Gasparyan (2007) conducted a theoretical exploration, investigating the influence of temperature variations on a solar cell's short-circuit current and open-circuit voltage, presenting potential pathways for efficiency improvement (Gasparyan, 2007). Maka & O'Donovan (2022) focused on triplejunction solar cells, examining the impact of thermal load on performance parameters and emphasizing the critical role of thermal management (Maka & O'Donovan, 2022). Lakshmi and Desappan (2014) delved into temperature effects on solar cells, offering insights into the influence of temperature on various parameters in solar PV systems and addressing challenges associated with temperature variations (Ponnusamy & Desappan, 2014).

Ebhota and Tabakov (2023) investigated the influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance, providing comparative insights into the performance of crystalline silicon (c-Si) and copper indium gallium selenide (CIGS) PV cells (Ebhota & Tabakov, 2023). Barron-Gafford et al. (2016) studied the temperature effect of photovoltaic cells, synthesizing previous research and discussing mechanisms and progress in mitigating temperature effects. Sun et al. (2022) addressed the photovoltaic heat island effect, revealing that larger solar power plants increase local temperatures, challenging theoretical models and raising concerns for large-scale installations (Sun et al., 2022). Arifin and team (2020) explored the effect of heat sink properties on solar cell cooling systems, focusing on passive cooling systems and introducing a heat sink with fins to address solar cell overheating, demonstrating enhanced cooling capacity (Arifin & Suyitno, 2020). Mesquita et al. (2019) assessed the temperature impact on perovskite solar cells under operation, concentrating on perovskite solar cells and highlighting challenges associated with thermal stability during operation (Mesquita et al., 2019).

Distinct from these individual studies, the current review synthesizes insights from this array of research, providing a comprehensive overview of recent advancements in the study of thermal effects on solar cells. It distinguishes itself by offering a focused lens on recent developments, a meticulous analysis of the latest research findings, and an emphasis on quantitative values for enhanced clarity (Hasan et al., 2023). By bridging gaps left by existing reviews, this comprehensive analysis contributes to a nuanced understanding of the complexities associated with thermal effects on solar cells. While the individual studies mentioned contribute valuable insights, the current review distinguishes itself in several key aspects. By consolidating findings from diverse studies, it provides a comprehensive overview of recent advancements in thermal effects on solar cells. Focusing specifically on recent developments, the review ensures an up-to-date analysis that reflects cutting-edge research in the field. In contrast to some existing reviews that offer broad overviews, the current review stands out with its commitment to a meticulous analysis of the latest research findings, providing insights into methodological approaches, results, and implications (Additional files 5, 6, 7, 8, 9).

Moreover, the current review places a strong emphasis on the importance of quantitative values for context, enhancing clarity and delivering a more data-driven and informative analysis. By synthesizing insights from various studies, the current review significantly contributes to a nuanced understanding of the complexities associated with thermal effects on solar cells. In essence, it serves as a bridge, addressing gaps left by existing reviews, and offers a timely, detailed, and comprehensive analysis of recent advancements in the study of thermal effects on solar cells.

This comprehensive review is organized to offer a comprehensive understanding of how thermal effects



Fig. 1 Comprehensive exploration of thermal effects on solar cells

impact the performance of solar cells. To facilitate a systematic exploration of this multifaceted topic, the article is divided into distinct sections, as illustrated in Fig. 1.

The comprehensive aim of this review is dual-fold: firstly, to foster a profound comprehension of how thermal effects intricately influence solar cell performance, and secondly, to provide guidance for advancing solutions and innovations that can amplify the efficiency and reliability of photovoltaic systems. Our specific objectives encompass elucidating the mechanisms through which temperature impacts the electrical characteristics of solar cells, reviewing and analyzing various experimental methods and techniques employed for thermal analysis, examining the diverse factors contributing to temperature variations in solar cell environments, exploring strategies and technologies for mitigating the adverse effects of temperature, showcasing real-world case studies illustrating the practical significance of thermal effects, and highlighting emerging trends and research directions poised to propel the field of solar cell technology towards enhanced efficiency and sustainability in solar energy generation.

Solar cell basics

In our quest to understand the influence of thermal effects on solar cell performance, it is vital to commence with the fundamentals of solar cell operation (Asdrubali & Desideri, 2018). Solar cells, also known as photovoltaic (PV) cells, are semiconductor devices that directly convert sunlight into electricity (Igliński et al. 2023; Dixit et al., 2023). The operation of these devices is rooted in the photovoltaic effect, a phenomenon discovered by Alexandre-Edmond Becquerel in 1839 and later elucidated by Albert Einstein in 1905, which earned him the Nobel Prize in Physics in 1921 (Mohan et al., 2023; Singh et al., 2023). The fundamental principles governing the operation of a solar cell can be succinctly outlined as follows. Firstly, sunlight, comprising discrete energy packets known as photons, strikes the solar cell's surface. Photon absorption takes place when these photons possess energy equal to or greater than the bandgap energy of the semiconductor material within the cell (Najm et al., 2023). Subsequently, the absorbed photons transfer their energy to electrons, elevating them from the valence band to the conduction band and generating electronhole pairs within the material. Capitalizing on the internal electric field within the semiconductor, the newly formed electron-hole pairs undergo separation, with



electrons migrating toward the n-type (negative) side and holes toward the p-type (positive) side. This separation initiates the flow of electrical current—a movement of electrons and holes—ultimately harnessed as electricity. The conductive metal contacts on the solar cell's surface collect this electrical current, rendering it available for various applications (Song et al., 2023).

Solar cell efficiency evolution: a historical timeline

The historical progress of solar cell efficiency, as depicted in Fig. 2, provides a comprehensive overview of the dynamic evolution of various solar cell technologies. This timeline graph spans from the early years of solar cell development in the 1950s to the present, highlighting key milestones and breakthroughs. Early years (1950s-1970s), the initial decades marked the foundational phase of solar cell technologies, predominantly centered around silicon-based cells. During this period, efficiencies were relatively modest, and research efforts were primarily directed at gaining a deeper understanding of semiconductor materials (Sun et al., 2023). Film Technologies (1980s–1990s), the timeline indicates a significant shift with the emergence of thin-film technologies, such as amorphous silicon and cadmium telluride (CdTe). These innovations not only introduced diversity to the solar market but also led to improvements in efficiency and manufacturing processes (Utkir, 2023). Advancements in the 2000s and 2010s showcased the rise of multi-junction and tandem cell technologies. These sophisticated designs allowed solar cells to capture a broader spectrum of sunlight, pushing the boundaries of efficiency further. The timeline (2010s-Present) reflects a recent surge in perovskite solar cells and other emerging technologies during the 2010s and the present. This surge signifies the ongoing quest for novel materials and techniques aimed at boosting efficiency and overcoming limitations associated with traditional solar cells (Adevinka Table 1 Types of solar cells and their applications

Type of solar cell	Application
Monocrystalline	Residential and commercial
Polycrystalline	Utility-scale installations
Thin-film	Building-integrated PV
Multi-junction	Concentrated solar power
Bifacial	Dual-sided solar panels

et al., 2023). The rightmost part of the (Present) provides a snapshot of the current state of solar cell efficiency. It serves as a visual representation of the coexistence of diverse technologies in the solar energy landscape, each contributing to the overall progress in harnessing solar power (Elumalai et al., 2016; Hughes et al., 2023). Key technological developments and shifts in solar cell types are represented in Fig. 2, showcasing the evolution of efficiencies over the years (Elumalai et al., 2016).

Different types of solar cells and their applications

Solar cells come in various types, each with its unique properties, advantages, and applications. The choice of solar cell type depends on factors such as efficiency, cost, and specific use cases. Table 1 outlines different types of solar cells and their primary applications. This discussion sets the stage for exploring the thermal effects on these different solar cell types.

Various types of solar cells are employed in diverse applications, each with its unique characteristics. Monocrystalline Silicon solar cells, crafted from singlecrystal silicon wafers, boast high efficiency but come with a higher production cost, making them commonly utilized in residential and commercial installations (Ngwashi & Tsafack, 2023). Polycrystalline Silicon cells, constructed from multiple silicon crystals, offer a cost-effective alternative with slightly lower efficiency compared to monocrystalline cells and find applications across various sectors, including residential and industrial settings (Ali et al., 2023; Bondoc & Eduardo., 2023). Within the category of Thin-Film Solar Cells, amorphous Silicon (a-Si) solar cells are characterized by thinness and lightness, making them suitable for flexible and portable applications, such as solar panels for backpacks and small electronic devices (Adevinka et al., 2023; Gao et al., 2023). Cadmium Telluride (CdTe) solar cells, known for their low manufacturing costs and competitive efficiency, are prevalent in large-scale utility solar farms (Dallaev et al., 2023; Limmanee et al., 2023). Copper Indium Gallium Selenide (CIGS) cells strike a balance between efficiency and cost and find applications in various settings, including building-integrated photovoltaics (BIPV) (Maalouf

Table 2 Factors affecting solar cell efficiency

Factor	Impact on efficiency
Temperature	Higher temperatures reduce efficiency
Solar Irradiance	Greater sunlight intensity leads to higher efficiency
Angle of Incidence	Optimal angles maximize efficiency
Dust and Dirt Accumu- lation	Reduces efficiency by blocking sunlight
Shading	Partial shading decreases efficiency

et al., 2023). Multi-Junction Solar Cells, reserved for specialized applications where high efficiency is paramount, comprise multiple layers of distinct semiconductor materials. Each layer is designed to capture a specific portion of the solar spectrum, and these cells are prevalent in space applications, concentrator photovoltaics (CPV), and high-efficiency terrestrial installations (Andres et al., 2023; Gibert-Roca et al., 2023). Organic Solar Cells, utilizing organic materials as the active layer, are known for their lightweight and flexibility. With the potential for low-cost production, they are primarily employed in portable and niche applications (Sun et al., 2023; Weitz et al., 2023).

Factors affecting solar cell efficiency

Table 2 highlights key factors influencing solar cell efficiency. Temperature has a negative impact, while higher solar irradiance and optimal angles increase efficiency. Dust, dirt, and shading can hinder efficiency by reducing the amount of sunlight reaching the solar cells.

The efficiency of solar cells, a critical factor in converting sunlight into electricity, is influenced by various factors. Material properties, particularly the bandgap energy of the semiconductor material, play a crucial role in determining the solar spectrum portion that can be absorbed (Kumar et al., 2023). Semiconductors with smaller bandgaps can capture a broader range of photons, including those with lower energy, but this may result in lower efficiency due to thermal losses. Additionally, higher carrier mobility within the material enhances charge separation and collection efficiency (Li et al., 2023). The relationship between bandgap energy and efficiency is intricate and depends on the specific semiconductor materials used. In solar cells, bandgap energy refers to the difference between the valence band and the conduction band, defining the range of photons the material can absorb. Materials with smaller bandgaps have a lower energy threshold for absorbing photons, allowing them to capture a broader spectrum, including lower-energy photons like infrared light. However, there are trade-offs associated with this characteristic. For instance, Amorphous Silicon (a-Si) serves as an example of a material with a smaller bandgap, around 1.7 eV. While a-Si can capture a broad range of photons, its efficiency in converting sunlight into electricity tends to be lower. This is attributed in part to higher thermalization losses, where excess energy, especially from photons with energy less than the bandgap, is lost as heat. In contrast, Monocrystalline Silicon (c-Si) exemplifies a material with a larger bandgap, approximately 1.1 eV. Although c-Si absorbs a narrower range of photons compared to a-Si, it tends to have higher conversion efficiency for the photons it does capture (Kumar et al., 2023; Li et al., 2023). In summary, the selection of bandgap in solar cell materials involves a trade-off between capturing a broad range of photons and achieving high conversion efficiency. While materials with smaller bandgaps can capture a broader spectrum, they may face challenges related to higher thermal losses, resulting in lower overall efficiency. On the other hand, materials with larger bandgaps may have a narrower absorption range but can achieve higher efficiency for the absorbed photons. The specific values and characteristics can vary among different semiconductor materials.

Temperature is a significant factor impacting solar cell efficiency, as elevated temperatures can lead to reduced performance, attributed to increased electron-hole recombination and resistance-a key thermal effect explored in this review (Wright et al., 2023; Failed, 2023a). The incident angle of sunlight and its intensity also contribute to efficiency variations. Solar tracking systems optimize incident angles, while sunlight intensity, varying with location and time of day, affects available energy for conversion (Almenabawy et al., 2023). Surface reflection and absorption are managed through anti-reflective coatings applied to solar cell surfaces, minimizing reflection and maximizing photon absorption. Manufacturing and design factors are critical, with defects and contaminations during manufacturing potentially hindering performance. Quality control processes are essential in addressing these issues. Additionally, solar cell design, encompassing layer arrangements, significantly impacts efficiency, with ongoing innovations continually enhancing performance (Carlson, 2023).

Quantitative insights into solar cell efficiency

Solar cell efficiency, a pivotal metric in evaluating photovoltaic technologies, exhibits a diverse range across different materials and designs. Crystalline silicon, a prevalent choice, showcases variations in efficiency. Monocrystalline silicon, known for its stability, typically achieves efficiency levels ranging from 15 to 22%. On the other hand, polycrystalline silicon, offering a costeffective alternative, falls within the efficiency range of

13% to 18%. Thin-film technologies contribute flexibility and cost advantages. Amorphous silicon (a-Si), a notable player, demonstrates efficiencies ranging from 6 to 12%. Another contender, cadmium telluride (CdTe), gains attention for cost-effectiveness, with reported efficiencies spanning 9% to 22%. Considered a promising player in the field, perovskite solar cells exhibit reported efficiencies surpassing 25%. Research efforts are actively focused on enhancing stability. In the realm of concentrated photovoltaics, multijunction solar cells achieve efficiencies exceeding 40%. These cells leverage multiple semiconductor layers to capture a broad spectrum of sunlight. Quantum dot solar cells, in the research phase, aim for higher efficiencies but lack standardized values at present (Kim et al., 2020; Shanmugam, 2020). Efficiency values aren't static; they vary based on geographical locations and environmental conditions. Ongoing technological advancements continue to push the boundaries, with efficiency values subject to updates. This exploration of solar cell efficiency provides a nuanced understanding, considering diverse materials, technologies, and the dynamic nature of research and development in the solar energy domain (Zambrano et al., 2021). The findings depicted in Fig. 3 (Saha et al., 2015) highlight a notable trend in the realm of photovoltaic devices, emphasizing that the efficiencies of solar cells employing new materials are currently not on par with traditional silicon solar cells. However, the data also underscore an optimistic perspective, as researchers worldwide remain hopeful. This optimism is rooted in the rapid advancements observed in the key parameters of higher-generation solar cells. Notably, the ongoing progress in these advanced solar cell technologies, coupled with the relatively low production costs of the materials used, fuels the anticipation



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for future breakthroughs that could potentially close the efficiency gap between traditional silicon solar cells and their innovative counterparts. This figure serves as a visual representation of the current landscape, encouraging further exploration and development in the pursuit of enhanced solar cell efficiency.

Thermal effects on solar cells

Solar cells are remarkable devices that harness the power of sunlight to generate electricity. However, they are not immune to the influence of temperature. In this section, we delve into the intricate relationship between thermal effects and solar cell performance. We explore the definition of thermal effects, their profound impact on solar cell efficiency, voltage, and current output, delve into the mechanisms behind thermal losses, and introduce relevant theoretical models and equations that underpin our understanding of this complex interaction (Al-Jumaili et al., 2019). Thermal effects in the context of solar cells refer to the changes in their electrical and optical properties due to variations in temperature. As solar cells operate, they invariably generate heat. This heat can originate from multiple sources, including the absorbed sunlight, resistive losses in the cell's electrical contacts, and even environmental factors. The temperature of a solar cell can fluctuate widely based on its location, time of day, and exposure to sunlight (Dwivedi et al., 2020). The influence of temperature on solar cell performance is multifaceted and can have both positive and negative effects. Understanding these effects is crucial for optimizing the efficiency and longevity of photovoltaic systems.

Impact of temperature on solar cell efficiency, voltage, and current output

Temperature exerts a noteworthy influence on solar cell efficiency, generally causing a decline as temperatures rise. This decline is chiefly attributed to two primary factors. Firstly, the open-circuit voltage (Voc) of a solar cell typically decreases with increasing temperature. Voc signifies the maximum voltage the cell can generate without a connected load. The reduction in Voc is linked to the rise in the intrinsic carrier concentration of the semiconductor material, leading to increased electron-hole recombination and a subsequent decrease in voltage output (Salimi et al., 2023; Shahariar et al., 2020). Secondly, the fill factor (FF), indicating a solar cell's effectiveness in converting sunlight into electricity, is also impacted by temperature. Higher temperatures tend to diminish FF due to increased resistive losses within the cell, resulting in an overall efficiency decrease (Elbar et al., 2019; Lakhdar & Hima, 2020). Illustrated in Fig. 4 is the correlation between solar cell efficiency and temperature. As temperature rises, efficiency experiences a decline attributed



Fig. 4 Solar cell efficiency vs. temperature (a, Solar Cell; b, Individual efficiencies vs temperature; c, Voltage vs junction dynamic velocity for different temperatures; d, photocurrent vs temperature; e, Open circuit voltage vs temperature for different base doping levels; and f, Open circuit voltage vs temperature for different base doping levels) (Ouédraogo et al., 2021)

to heightened electron-hole recombination rates and alterations in the bandgap properties of materials. This awareness of temperature-dependent behavior is pivotal for optimizing solar cell performance and implementing effective cooling strategies (Ouédraogo et al., 2021).

Temperature plays a crucial role in shaping the electrical characteristics of solar cells, impacting both voltage and current output. Regarding voltage, the open-circuit voltage (Voc) diminishes with rising temperatures, influencing the maximum power point voltage (Vmpp). Vmpp, representing the voltage at which the solar cell achieves its peak power output, undergoes a decrease due to a shift in the voltage-temperature coefficient caused by temperature increases (An et al., 2019). In terms of current output, solar cells exhibit variations with changes in temperature. Elevated temperatures generally result in an increase in the short-circuit current (Isc), signifying the maximum current output under shortcircuit conditions. This rise is attributed to heightened carrier concentrations and improved mobility in the semiconductor material at higher temperatures (Zhao et al., 2020a).

Mechanisms behind thermal losses in solar cells

Understanding the impact of temperature on solar cell performance requires delving into the underlying mechanisms governing thermal losses. Several key mechanisms contribute to the reduction in efficiency and voltage. Auger Recombination becomes more significant at higher temperatures. This process involves the interaction of three charge carriers-two electrons and one hole-resulting in the non-radiative recombination of carriers. The increased likelihood of carriers participating in the Auger process at elevated temperatures leads to a decrease in the overall efficiency of the solar cell (Adeeb et al., 2019; Fathi & Parian, 2021). Shockley-Read-Hall (SRH) Recombination is another crucial mechanism that intensifies at higher temperatures. It occurs when charge carriers are trapped at defect states within the semiconductor material, leading to non-radiative recombination. With increased thermal energy, more carriers can overcome trap energy barriers, increasing the likelihood of recombination through the SRH process and reducing the solar cell's efficiency (Gupta et al., 2022). Increased Carrier Mobility at elevated temperatures can enhance current output but exacerbate recombination losses, especially near the electrical contacts. Carrier mobility refers to how efficiently charge carriers move through the semiconductor material. The increased thermal energy enables carriers to move more freely, leading to enhanced electrical conductivity. However, this increased mobility can raise the likelihood of recombination events, particularly near the contacts, resulting in reduced overall efficiency (Jošt et al., 2020). Dark current, representing the current generated within a solar cell in the absence of light, tends to increase with temperature. This rise is primarily due to thermally generated carriers. At higher temperatures, thermal energy excites electrons, creating additional charge carriers that contribute to dark current. While more prominent in the absence of light, dark current also influences the electrical characteristics of the solar cell under illuminated conditions, potentially reducing overall efficiency (Markvart, 2022).

These mechanisms collectively contribute to the impact of temperature on solar cell performance, highlighting the complex interplay between thermal effects and the efficiency, voltage, and current output of photovoltaic systems. It is imperative to consider these mechanisms when designing solar cells and implementing strategies to mitigate the adverse effects of temperature, as understanding these underlying processes is essential for optimizing solar cell performance. Cutting-edge research has elucidated the intricate mechanisms behind thermal losses in solar cells. At elevated temperatures, Auger recombination, a process involving the interaction of three charge carriers, has been identified as a significant contributor to non-radiative recombination, impacting the lifetime of charge carriers and overall efficiency (Subramani et al., 2021). Shockley-Read-Hall (SRH) recombination mechanisms, particularly prevalent at higher temperatures, involve charge carriers trapped at defect states within the semiconductor material, leading to nonradiative recombination (Lee et al., 2020). The exploration of increased carrier mobility at higher temperatures has uncovered a dual impact, enhancing current output while exacerbating recombination losses, especially near the cell contacts. Furthermore, research has delved into the phenomenon of higher dark current at elevated temperatures, mainly attributed to the thermally generated carriers, posing challenges to maintaining overall cell efficiency (Shu et al., 2022). Figure 5 illustrates the key mechanisms contributing to thermal losses in solar cells. Auger recombination, Shockley-Read-Hall (SRH) recombination, increased carrier mobility, and higher dark current are explored, providing a visual representation of the complexities involved (Shang & Li, 2017). Figure 5 visually encapsulates the intricate mechanisms leading to thermal losses in solar cells. Auger recombination, SRH recombination, increased carrier mobility, and higher dark current are fundamental processes explained in the preceding sections. This visual aid enhances comprehension, serving as a quick reference for readers exploring the nuanced interactions within solar cell materials.

Relevant theoretical models and equations

Understanding the impact of temperature on solar cell performance relies on theoretical models and equations that describe these complex interactions. The Shockley equation describes the current–voltage (I–V) characteristics of a solar cell. It combines the effects of temperature, voltage, and other factors to predict the cell's electrical behavior. The equation is given as (Díaz, 2022):

$$I = I_{ph} - I_0(exp\bigg(\frac{qV}{nkT}\bigg) - 1)$$

where: *I* is the total current through the cell, I_{ph} is the photocurrent (current generated by absorbed light), I_0 is the dark current (current in the absence of light), *q* is the elementary charge, *V* is the voltage across the cell, *n* is the ideality factor, *k* is Boltzmann's constant and *T* is the absolute temperature.

The Shockley–Queisser limit is a theoretical model that defines the maximum achievable efficiency of a



Fig. 5 Mechanisms behind thermal losses in solar cells (Shang & Li, 2017)

single-junction solar cell as a function of the semiconductor bandgap and temperature. It provides insights into the fundamental efficiency limits of solar cells and how temperature affects these limits (Markvart, 2022). These equations describe the dependence of carrier concentrations (electrons and holes) on temperature, which is crucial for understanding the variation in open-circuit voltage and short-circuit current with temperature (Das et al., 2022). In conclusion, thermal effects on solar cells are a complex yet critical aspect of photovoltaic technology. Understanding the impact of temperature on solar cell efficiency, voltage, and current output is essential for optimizing the performance of photovoltaic systems in diverse environmental conditions. By comprehending the

Experimental technique	Latest advancements	Future outlook
Thermal Imaging	Real-time monitoring capabilities with high spatial resolu- tion (Sarath et al., 2023; Sharma et al., 2019) Non-invasive and non-contact technology (Sarath et al., 2023) Detailed temperature mapping of solar cell surfaces dur- ing operation (Sharma et al., 2019)	Continued enhancement of spatial resolution for finer tem- perature mapping Integration with machine learning algorithms for automated anomaly detection Cost reduction initiatives to improve accessibility for a broader spectrum of researchers (Ajayi & Abegunde, 2022)
Calorimetry	Accurate measurement of heat generation in solar cells (Fang et al., 2023) Determination of thermal conductivity in solar cell materi- als (Fang et al., 2023) Capability for steady-state and transient thermal analysis (Fang et al., 2023)	Streamlining of experimental setups for broader adoption Development of advanced calorimetric techniques to cap- ture rapid temperature changes more effectively Integration with simulations for predictive analysis of solar cell thermal behavior (Mohammadnia & Ziapour, 2020)
Temperature-Dependent Characterization	Comprehensive data on electrical response under different thermal conditions (Failed, 2021) Direct assessment of temperature impact on efficiency, voltage, and current (Malik et al., 2021) Applicability in existing solar cell testing setups (Failed, 2021)	Improved temperature control in experimental setups for enhanced accuracy Advancements in simultaneous characterization at multiple temperature points Integration with artificial intelligence for predictive modeling of solar cell performance (Shrestha, 2020)

Table 3 Advances in experimental techniques for thermal assessment

mechanisms behind thermal losses and utilizing theoretical models and equations, researchers and engineers can work towards enhancing the efficiency and reliability of solar cell technology, bringing us closer to the goal of sustainable and efficient solar energy generation.

Advancements in experimental techniques

Recent research has witnessed remarkable progress in refining experimental techniques for thermal assessment of solar cells. Advanced thermal imaging technologies now provide not only high spatial resolution but also real-time monitoring capabilities (Table 3). This empowers researchers to capture dynamic temperature changes during operation with unprecedented detail (Alhmoud, 2023). Calorimetry techniques have evolved, enabling accurate measurements of heat generation and facilitating a deeper understanding of heat dissipation mechanisms within solar cell materials (Hellin & Loreto., 2023). Temperature-dependent characterization methods, especially those integrating with existing testing setups, now offer more comprehensive insights into the electrical response of solar cells under varying thermal conditions (Rahmani et al., 2021). The latest advancements in experimental techniques are poised to revolutionize the understanding of thermal effects on solar cells. These innovations bring about higher precision, offering detailed insights that were previously challenging to attain. Thermal imaging's real-time monitoring and high spatial resolution provide a dynamic view of temperature changes during operation, laying the foundation for targeted interventions. Calorimetry, with its accurate heat measurement capabilities, is crucial for unraveling the intricate mechanisms of heat dissipation within solar cell materials. The evolution toward steady-state and transient thermal analysis enhances our understanding of the dynamic thermal behavior of solar cells. Temperature-dependent characterization, integrating seamlessly into existing testing setups, offers a practical approach to assess the electrical response under various thermal conditions. Looking ahead, these advancements set the stage for more sophisticated experimentation. Further integration with machine learning algorithms and simulations promises predictive capabilities, enabling researchers to anticipate and address thermal challenges effectively. Additionally, cost reduction initiatives will democratize access to these technologies, fostering a collaborative environment for advancing solar cell research.

Future outlook and implications for the solar energy industry

Looking ahead, the implications of these recent findings are profound for the solar energy industry. The advancements in experimental techniques offer more accurate and detailed thermal assessments, crucial for optimizing solar cell performance in real-world environmental conditions. The mechanistic insights into thermal losses provide a foundation for developing targeted strategies to mitigate efficiency reductions, thereby enhancing the reliability and longevity of solar technologies. The integration of these latest research findings into solar cell design and manufacturing processes holds the potential to unlock new frontiers in efficiency improvement. Tailoring solar cells to better withstand and adapt to temperature variations, guided by a deeper understanding of thermal effects, will contribute significantly to the industry's quest for sustainable and efficient solar energy generation. In conclusion, the latest research in thermal effects on solar cells marks a paradigm shift, emphasizing precision in assessment techniques and uncovering intricate mechanisms (Li et al., 2021). As we look to the future, these findings not only deepen our understanding but also chart a course toward more resilient and efficient solar technologies, playing a pivotal role in the global transition toward sustainable energy sources. The future implications of recent research findings are farreaching for the solar energy industry. The precision afforded by advancements in experimental techniques holds the potential for more reliable solar cell optimization. Broader accessibility ensures that these benefits are not confined to a select few but are disseminated across the solar cell research community, fostering collaboration and shared knowledge (Table 4). Mechanistic insights into thermal losses provide a roadmap for targeted interventions to mitigate efficiency reductions. This knowledge serves as a foundation for developing adaptive solar cell designs capable of withstanding and adapting

 Table 4
 Future outlook and implications for the solar energy industry

Aspect of research findings	Future implications
Advancements in techniques	Improved precision in thermal assessment techniques contributes to more reliable solar cell performance optimization Broader accessibility enhances collaboration and knowledge dissemination in the solar cell research community
Mechanistic insights	In-depth understanding of thermal losses informs targeted strategies to mitigate efficiency reductions Foundations for developing adaptive solar cell designs that can withstand and adapt to temperature variations
Integration in industry	Integration of latest research findings into solar cell design and manufacturing processes to improve efficiency Tailoring solar cells for enhanced resilience to temperature variations, contributing to sustained efficiency and longevity

to temperature variations. The integration of these findings into solar cell manufacturing processes holds the key to sustained efficiency and longevity, aligning with the industry's pursuit of more robust and reliable solar technologies.

Heat effects and heat transfer in solar systems

In any solar energy system, the conversion of sunlight into electricity is crucial, but it isn't perfectly efficient and can lead to heat generation. This section explores heat effects, transfer mechanisms, and losses associated with components like charge controllers, inverters, and wiring (Wei et al., 2021). Charge controllers regulate energy flow from solar panels to batteries, generating heat due to electrical resistance. Inverters convert DC to AC, introducing heat in semiconductors. Wiring and conductors experience resistive losses, producing heat (Din et al., 2023; Lipiński et al., 2021; Ma et al., 2021). Effective heat management is vital to prevent overheating. Conduction transfers heat through direct contact, using metal heat sinks to dissipate it. Convection involves fluid movement, with systems employing fans or liquid cooling for heat dissipation. Radiation uses electromagnetic waves, and solar components may incorporate radiative cooling techniques like heat-reflective coatings (Aghaei et al., 2020; Aslam et al., 2022; Nkounga et al., 2021). Heat can lead to energy losses and reduced efficiency. Electrical losses occur due to resistance in components like wires, cables, and connectors. Inverters, especially older models, may experience significant heat-related losses. High operating temperatures can reduce battery efficiency and lifespan (Hernández-Callejo et al., 2019; Sarath et al., 2023; Sharma et al., 2019). Efforts to mitigate heat effects include designing components to minimize heat generation and optimize dissipation. Active cooling systems, such as fans and liquid cooling, can be integrated into solar components. Regular monitoring and maintenance practices, along with choosing high-efficiency inverters and using appropriate wiring, contribute to preventing overheating and improving system efficiency (Fang et al., 2023; Zhou et al., 2015). In conclusion, heat generation, heat transfer, and losses resulting from the operation of solar system components are essential considerations for optimizing the efficiency and reliability of solar energy systems. Effective heat management techniques, along with advances in component design and technology, contribute to the overall performance and sustainability of solar power installations. Properly addressing heat effects ensures that solar systems continue to harness the sun's energy efficiently and effectively for clean and renewable electricity generation.

Table 5 offers an overview of heat effects, transfer mechanisms, losses, and mitigation strategies in various solar system components: Charge Controllers generate heat through electrical resistance, with conduction and convection facilitating heat transfer. Energy losses occur, impacting system efficiency. Mitigation involves using efficient semiconductors, cooling systems, and regular monitoring. Inverters produce heat during the DC to AC conversion, transferred through conduction and convection. Energy losses result from heat-related inefficiencies. Selecting high-efficiency inverters, implementing cooling systems, and efficient component design address heat effects. Wiring and Conductors experience heat generation due to electrical resistance, with conduction and convection causing energy losses. Proper sizing, rating of wiring, and efficient component design minimize these losses. Batteries in off-grid systems generate heat during charge/discharge cycles, with conduction and convection as heat transfer mechanisms. Issues include reduced efficiency and shortened lifespan, addressed through temperature monitoring and battery cooling systems. Solar

Table 5	Heat	: effects	and	heat	transfer	in	solar	systems
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Solar system component	Heat generation mechanism	Heat transfer mechanisms	Heat-related losses	Mitigation strategies
Charge Controllers	Electrical resistance	Conduction, Convection	Energy losses	Component design with effi- cient semiconductors, cooling systems, regular monitoring
Inverters	DC to AC conversion	Conduction, Convection	Energy losses	High-efficiency inverter selec- tion, cooling systems, efficient component design
Wiring and Conductors	Electrical resistance	Conduction, Convection	Energy losses	Proper sizing and rating, efficient component design
Batteries (Off-grid)	Charge/discharge cycles	Conduction, Convection	Reduced efficiency, reduced lifespan	Temperature monitoring, battery cooling systems
Solar Panels	Sunlight absorption	Conduction, Convection, Radiation	Reduced efficiency	Solar panel design, radiative cooling, cleaning and mainte- nance



Fig. 6 a Heat transfer mechanisms in solar systems. b Heat transfer mechanism from back side of solar panels to thermo-electric cells through air-cooling mechanism. c Heat transfer mechanism from back side of solar panels to thermo-electric cells through water-cooling mechanism. (Malik et al., 2021)

Panels absorb sunlight, leading to heat generation transferred through conduction, convection, and radiation. Reduced panel efficiency is a concern, addressed through solar panel design, radiative cooling techniques, and regular cleaning and maintenance. Understanding these heat effects, transfer mechanisms, and losses is crucial for optimizing solar energy systems. Mitigation strategies, ranging from component design to cooling systems and monitoring, are employed to manage heat effectively and ensure the sustained performance of solar systems.

Figure 6 visually depicts heat transfer mechanisms in solar systems, illustrating how heat is generated and managed within different components. Heat generation occurs in charge controllers (electrical resistance), inverters (DC to AC conversion), wiring and conductors (electrical resistance), batteries (charge/discharge cycles), and solar panels (sunlight absorption). Conduction occurs through direct contact, convection through fluid movement, and radiation as electromagnetic waves emission. The figure shows heat transfer between components and the environment. For instance, charge controllers dissipate heat through conduction and convection, while inverters may use cooling systems. Solar panels utilize radiation for heat dissipation. Mitigation strategies, highlighted in the figure, include efficient component design, cooling systems (fans or liquid cooling), and regular temperature monitoring. Figure 6a underscores the importance of managing heat effects for system efficiency and reliability. Figures 6b and 3c demonstrate heat transfer from the backside of solar panels to the hot side of TEC, using air-cooling and water-cooling mechanisms, providing a reference for addressing thermal challenges in solar energy installations (Malik et al., 2021).

Table 6 Advantages and limitations of thermal imaging

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Non-invasive	High spatial resolution	Real-time monitoring	Surface measurement	Cost	Environmental conditions	Non-invasive	High spatial resolution
Thermal imaging is non-invasive and non- contact, suitable for capturing temperature distributions without altering solar cell opera- tion (Sarath et al., 2023)	Modern thermal imaging cam- eras offer high spatial resolu- tion, allowing detailed tem- perature map- ping of solar cell surfaces (Sharma et al., 2019)	Real-time tem- perature data can be obtained, enabling the observa- tion of dynamic temperature changes dur- ing operation (Sharma et al., 2019)	Primarily captures surface temperatures, less effective at assessing temperature gradients within the bulk of a solar cell (Sarath et al., 2023; Sharma et al., 2019)	High-quality thermal cameras can be expensive, limiting acces- sibility for some researchers	Weather conditions, such as wind and ambient temperature, can influence thermal imaging results, neces- sitating careful experimental setup and analy- sis (Zhou et al., 2015)	Thermal imaging is non-invasive and non- contact, suitable for capturing temperature distributions without altering solar cell opera- tion (Sarath et al., 2023)	Modern thermal imaging cameras offer high spatial resolution, allow- ing detailed temperature map- ping of solar cell surfaces (Sharma et al., 2019)

Experimental methods for thermal analysis

The study of thermal effects on solar cells is a critical aspect of optimizing their performance and efficiency. Experimental techniques play a vital role in understanding how temperature variations influence solar cell behavior. In this section, we explore various experimental methods used to study thermal effects on solar cells, including thermal imaging, calorimetry, and temperature-dependent characterization. We will also highlight the advantages and limitations of each method, providing insights into their applicability and contributions to the field.

Various experimental techniques

Understanding various experimental techniques is vital for assessing thermal effects on solar cells. Thermal imaging, characterized by high spatial resolution, visually represents temperature variations, aiding in pinpointing areas of concern (Table 6). Figure 7a illustrates temperature distribution across a solar cell surface, providing insights into localized thermal effects. The color gradient depicts varying temperatures, with a minimum temperature difference of 0.68 K between the center and corresponding edge (Fig. 7a) and a maximum difference of 1.2 K between the center and corner (Fig. 7b) (Zhou et al., 2015).

Calorimetry, a crucial technique, provides accurate measurements of heat generated by solar cells, enabling a precise assessment of thermal effects (Table 7).

Temperature-dependent characterization techniques, explored in Table 8, play a significant role in understanding and assessing thermal effects on solar cells.

Advantages and limitations of each method

Table 9 discussing the advantages and limitations of thermal imaging aids researchers in making informed

decisions when selecting this technique for assessing thermal effects on solar cells.

Understanding the advantages and limitations (Table 10) of calorimetry assists researchers in evaluating its suitability for assessing thermal effects on solar cells.

Analyzing the advantages and limitations (Table 11) of temperature-dependent characterization helps researchers in selecting suitable methods for assessing thermal effects on solar cells.

In conclusion, understanding the thermal effects on solar cells is crucial for optimizing their performance in diverse environmental conditions. Experimental techniques such as thermal imaging, calorimetry, and temperature-dependent characterization offer valuable insights into how temperature variations influence solar cell behavior. Each method has its advantages and limitations, and researchers must choose the most suitable approach based on their specific research goals and available resources. Ultimately, these experimental techniques contribute to the ongoing efforts to enhance the efficiency and reliability of solar cell technology, further advancing the utilization of solar energy as a sustainable power source.

Factors influencing thermal effects

The thermal performance of solar cells is intricately linked to numerous external and internal factors. A comprehensive understanding of these elements is imperative for the optimization of efficiency and reliability in solar energy systems. This section delves into the key elements influencing thermal effects on solar cells.

External factors affecting solar cell temperature

External factors, such as climate, geographic location, and installation parameters, significantly impact the temperature of solar cells. In Table 12, we explore the impact of climate and weather conditions on solar

cell temperature, considering factors such as temperature extremes, seasonal variations, and cloud cover. In regions characterized by extreme temperatures, such as hot deserts or cold climates, solar cells may undergo variations in efficiency (Osma-Pinto & Ordóñez-Plata, 2019). The dynamic response of solar cells to temperature extremes is a critical consideration for system designers. Higher temperatures, typical in hot climates, can lead to increased thermal losses, potentially impacting the overall efficiency of the solar cell. Conversely, in extremely cold conditions, solar cells may experience reduced efficiency due to the constraints imposed by low temperatures. Seasonal changes play a pivotal role in influencing solar cell temperature. During winter in cold climates, solar cells may encounter reduced efficiency due to the colder temperatures (Salamah et al., 2022). Cold weather can affect the performance of solar cells by altering the behavior of charge carriers and increasing resistive losses. On the other hand, in hot climates during the summer, solar cells may face thermal losses. The trade-off between seasonal variations and optimal performance highlights the importance of considering regional climatic conditions in solar energy system planning. Cloudy or overcast conditions introduce another layer of complexity to solar cell temperature regulation. Reduced sunlight during cloudy conditions impacts both the temperature of the solar cell and its electricity generation efficiency (Weaver et al., 2022). The limited sunlight reaching the solar cell not only affects its temperature but also reduces the amount of energy available for conversion. Cloud cover, therefore, represents a significant external factor influencing solar cell temperature and, consequently, the overall performance of the solar energy system. Table 12 underscores the dynamic and multifaceted nature of solar cell temperature regulation in response to climate and weather conditions. The identified factors emphasize the trade-offs between extreme conditions and optimal performance. System designers and planners must carefully weigh these considerations to enhance the efficiency and reliability of solar energy systems, particularly in diverse environmental contexts. As the solar industry continues to expand into various geographic regions, a nuanced understanding of these climate-related influences becomes increasingly crucial for the successful implementation of solar energy technologies.

Table 13 delves into the influence of geographic location, specifically considering latitude and altitude, on solar cell temperature. Here, we examine the key considerations and discuss the implications for system planning. The proximity to the equator, expressed in terms of latitude, is a crucial determinant of solar cell temperature (Din et al., 2023). Closer proximity to the equator generally results in higher temperatures. Solar installations located near the equator receive more direct sunlight throughout the year, contributing to increased temperatures of solar cells. This temperature elevation is a vital aspect for system planners to consider, as it directly impacts the efficiency and overall performance of solar energy systems. The latitude factor highlights the need for tailored strategies and technologies in regions with higher temperatures to mitigate potential thermal losses. Altitude, or the elevation above sea level, is another geographic factor influencing solar cell temperature (Din et al., 2023). Higher altitudes tend to have lower average temperatures due to the cooler air at higher elevations. The impact of altitude on solar cell temperature is an essential consideration for installations in mountainous or elevated regions. While lower temperatures can be advantageous for solar cell efficiency, other factors, such as the potential for increased solar radiation exposure at higher altitudes, need to be weighed. System planners must balance the benefits and challenges associated with altitude to optimize the performance of solar energy systems. The discussion surrounding Table 13 emphasizes the significance of geographic location, specifically considering latitude and altitude, in influencing solar cell temperature. The observations underscore the importance of incorporating these geographical factors into system planning for solar energy installations. The latitude-altitude dynamics provide valuable insights for system designers, helping them tailor solar energy technologies and strategies to suit the specific climatic conditions of a given location. This nuanced approach is crucial for enhancing the efficiency, reliability, and overall success of solar energy systems in diverse geographic settings.

Table 14 provides insights into the impact of installation angle and orientation on solar cell temperature, emphasizing considerations related to tilt angles and panel orientations. Here, we delve into the key factors and discuss their implications for mitigating thermal effects. The tilt angle of solar panels plays a crucial role in determining solar cell temperature (Atsu et al., 2020). By adjusting the tilt angle based on the sun's position, solar cells can minimize their temperature, especially in hot climates. This adjustment optimizes the angle at which sunlight strikes the panels, reducing the absorption of excessive heat. The consideration of tilt angles is particularly relevant in regions with high temperatures, as it offers a practical and efficient means to regulate solar cell temperature. The importance of this factor lies in its ability to enhance overall energy yield by maintaining optimal operating conditions. The orientation of solar panels, whether facing north-south or east-west, significantly influences the amount of sunlight received and, consequently, solar cell temperature



Fig. 7 a Temperature distribution across a solar cell, b Direction parallel to sideline and c diagonal direction (Zhou et al., 2015)

(Atsu et al., 2020). The direction in which panels are oriented determines their exposure to direct sunlight. System planners must strategically decide the orientation based on the solar path and prevailing climate conditions. Optimizing panel orientation is a key aspect of thermal management, ensuring that solar cells receive sunlight effectively without being subjected to excessive heating. The discussion of orientation underscores the importance of thoughtful planning in maximizing energy production while minimizing thermal impacts. Table 14 underscores the significance of optimizing tilt angles and panel orientations to mitigate thermal effects on solar cells. The considerations related to tilt angle adjustments and panel orientations provide practical strategies for system planners to regulate solar cell temperature. By strategically addressing these factors, it becomes possible to achieve a balance between energy efficiency and thermal management.

Internal factors within solar cell materials and designs

Internal factors related to solar cell materials, designs, encapsulation, electrical configuration, and tracking systems significantly influence thermal effects. Table 15 provides a comprehensive overview of the impact of solar cell material on thermal performance, focusing on factors such as material bandgap and thermal conductivity. The internal characteristics of solar cell materials play a crucial role in shaping their thermal behavior, and this discussion aims to shed light on the considerations presented in the table. The bandgap of solar cell materials significantly influences their ability to absorb photons, and this, in turn, affects their susceptibility to thermal losses (An et al., 2019). Materials with smaller bandgaps can absorb lower-energy photons, expanding their absorption spectrum but potentially making them more prone to thermal losses. The discussion around material bandgap underscores the delicate balance that must be struck between maximizing photon absorption and minimizing thermal effects. System designers and material scientists must carefully consider this trade-off to optimize the thermal performance of solar cells. This consideration becomes particularly important in environments with varying temperature conditions, where the material's response to thermal stress plays a critical role in overall efficiency. The thermal conductivity of solar cell materials is a key determinant of their ability to manage temperature variations effectively (An et al., 2019). Materials with higher thermal conductivity can efficiently dissipate heat, contributing to better thermal management within the solar cell. This characteristic becomes crucial in scenarios where solar cells are subjected to fluctuating environmental temperatures. The discussion on material thermal conductivity emphasizes the importance of selecting materials that strike a balance between their electrical properties and thermal behavior. Achieving a favorable compromise allows for optimal solar cell performance in diverse climatic conditions. Table 15 delves into the internal factors of solar cell materials and their impact on thermal performance. The discussion highlights the intricate trade-offs involved in choosing materials with specific bandgaps and thermal conductivities. Careful consideration of these factors is paramount for system designers and researchers seeking to enhance the efficiency and reliability of solar cells.

Figure 8 (Sze, 1981) provides a comprehensive view of ideal solar cell efficiency concerning the band gap energy, considering different spectral distributions and power densities. The plot illustrates the efficiency variations under the spectral distributions AM0, AM1.5 at 1 sun, and AM1.5 at 1000 suns. The data underscores the critical role of band gap energy in determining the optimal efficiency of solar cells under varying solar conditions. For instance, the chart reveals the influence of band gap

Accurate measurement	Thermal conductivity	Steady-state and transient analysis	Complex setup	Localized measurement	Thermal inertia
Provides accurate measurements of heat generated by a solar cell, allow- ing for precise assess- ment of thermal effects	Can determine the thermal con- ductivity of solar cell materials, crucial for understanding heat dissipation mechanisms	Allows for both steady-state and transient thermal analysis, facilitating a comprehensive understanding of thermal behavior (Fang et al., 2023)	Experiments often require specialized equipment and set- ups, making them more challenging and time-consuming to perform	Measurements are typically local- ized and may not capture tem- perature variations across the entire solar cell	Rapid temperature changes may not be captured adequately due to the heat accumulation and dissipation nature of calo- rimetry (Malik et al., 2021)

Table 7 Advantages and limitations of calorimetry

energy on efficiency, showcasing how different band gap values respond to sunlight at different power densities. This insight is valuable for researchers and engineers aiming to design solar cells tailored to specific environmental conditions and power requirements. It highlights the trade-offs between band gap energy and efficiency, emphasizing the need for a nuanced approach in solar cell design to achieve optimal performance across diverse operational scenarios.

Table 16 provides a comprehensive overview of how various design elements influence thermal effects in solar cells. The internal factors within solar cell designs, such as anti-reflective coatings, back-side reflectors, cell thickness, and bypass diodes, play a crucial role in shaping the thermal performance of the solar cell. This discussion aims to provide insights into the considerations presented in the table. The incorporation of anti-reflective coatings in solar cell design serves as an effective strategy to reduce the absorption of sunlight, consequently lowering the cell temperature (Sze, 1981). By minimizing sunlight absorption, anti-reflective coatings contribute to temperature regulation and enhance the overall performance of the solar cell. This discussion underscores the positive impact of anti-reflective coatings in mitigating thermal effects, especially in environments where excessive heating may pose challenges to efficiency. Back-side reflectors, as outlined in Table 16, redirect unabsorbed sunlight back into the solar cell, potentially increasing its temperature (Sze, 1981). This design element introduces a nuanced aspect to thermal effects, as the redirection of sunlight may lead to localized heating. System designers must carefully weigh the benefits and drawbacks of incorporating back-side reflectors, considering the specific environmental conditions in which the solar cells will operate. The discussion emphasizes the need for a comprehensive understanding of the thermal consequences associated with different design choices. The thickness of solar cells, as presented in Table 16, influences their thermal mass, impacting the rate of temperature changes and differences across the cell (Gupta et al., 2019). Thicker cells exhibit higher thermal mass, resulting in slower temperature changes but potentially greater temperature variations within the cell. This consideration highlights the importance of balancing thermal mass with the desired rate of response to environmental temperature fluctuations. System designers must tailor cell thickness to the specific requirements of the intended operating conditions, aiming for optimal thermal performance. Bypass diodes, as discussed in Table 16, serve as a mitigation strategy for hotspots and thermal effects by allowing current to bypass overheating or shaded cells (Gupta et al., 2019). The incorporation of bypass diodes contributes to the overall resilience of solar panels in diverse conditions, enhancing their performance and longevity. The discussion emphasizes the critical role of bypass diodes in managing thermal effects and maintaining the efficiency of solar cell arrays, especially in scenarios where cells may experience non-uniform

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lable 8	Advantages and	d limitations of	temperature-	dependent	characterization

Comprehensive data	Direct relevance	Applicability to existing testing	Limited temperature control	Surface effects	Time-consuming
Techniques provide comprehensive data on the electrical response of solar cells under different thermal conditions (Failed, 2021)	Directly assess the impact of tem- perature on solar cell electrical character- istics, including effi- ciency, open-circuit voltage, short-circuit current, and fill factor (Malik et al., 2021)	Can be integrated into existing solar cell testing setups, making it a practical choice for research and development (Failed, 2021)	Some experimental setups may have lim- ited control over tem- perature variations, affecting the accu- racy and repeatability of measurements (Grant & O'Dwyer, 2207)	Focuses primarily on the electrical response and may not provide insights into localized tem- perature variations (Grant & O'Dwyer, 2207)	Conducting experiments at mul- tiple temperature points can be time-consuming (Ortega, 2022)

(Zhao et al., 2020b)

Non-invasive	High spatial resolution	Real-time monitoring	Surface measurement	Cost	Environmental factors
Thermal imaging is non-invasive, making it suitable for monitoring solar cell temperatures during operation without interfering with performance	Offers high spatial resolution, allowing for detailed tempera- ture mapping of solar cell surfaces (Zhao et al., 2020b)	Provides real-time temperature data, enabling dynamic temperature analysis (Costanza, 2022)	Primarily captures surface temperatures, limiting its ability to assess tempera- ture gradients within the bulk of solar cells (Zhao et al., 2020b)	High-quality thermal cameras can be expensive, restricting availability for some researchers (Polo- Mendoza et al., 2023)	Weather conditions and envi- ronmental factors can influ- ence results, requiring careful experimental setup and analysis (Polo-Mendoza et al., 2023)

sunlight exposure. Table 16 offers valuable insights into the influence of solar cell design on thermal effects. The discussion emphasizes the dual nature of certain design elements, such as back-side reflectors, and underscores the need for a nuanced approach in optimizing solar cell performance. Design choices play a pivotal role in either mitigating or exacerbating thermal effects, and a thoughtful consideration of these factors is essential for advancing the efficiency and reliability of solar cells in varying environmental conditions.

Table 17 provides a comprehensive overview of the factors related to encapsulation and packaging that influence the thermal performance of solar cells. This discussion aims to delve into the considerations outlined in the table, shedding light on the crucial role of encapsulation and packaging in managing solar cell temperature. As highlighted in Table 17, the choice of encapsulation materials significantly impacts the ability of solar cells to dissipate heat effectively. The materials must possess good thermal conductivity to facilitate the efficient transfer of heat away from the solar cells (Yue et al., 2021). Effective encapsulation ensures that heat generated during the operation of solar cells is adequately conducted away, preventing thermal buildup that could compromise the cells' efficiency and reliability. The discussion underscores the importance of selecting materials with superior thermal conductivity in the encapsulation process to optimize thermal performance. Proper ventilation and cooling systems, as indicated in Table 17, play a critical role in maintaining optimal temperatures for solar cells (Yue et al., 2021). In solar installations, where temperature regulation is essential for sustained performance, effective ventilation and cooling become paramount. These systems help dissipate excess heat, preventing the solar cells from reaching temperatures that could adversely affect their efficiency and longevity. The discussion emphasizes the need for well-designed ventilation and cooling mechanisms as integral components of solar cell systems, contributing to the overall thermal management strategy. Table 17 underscores the significance of encapsulation and packaging in influencing the thermal performance of solar cells. The discussion emphasizes the dual role of encapsulation materials in providing structural support and facilitating efficient heat dissipation. The choice of materials and the implementation of ventilation and cooling systems are pivotal considerations in optimizing solar cell temperature. A thoughtful approach to encapsulation and packaging design contributes to the overarching goal of enhancing the efficiency and reliability of solar cells, particularly in the face of dynamic environmental conditions.

Table 18 provides a succinct overview of the influence of electrical and wiring configurations on the temperature of solar cells. This discussion delves into the considerations outlined in the table, emphasizing how the arrangement of solar cell connections and the efficiency of inverters impact the thermal performance of the entire solar energy system. The choice between series

Table 10	Advantages and limitations of calorimetry	
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Accuracy	Thermal	Steady-state and	Complex setup	Localized	Thermal inertia
	conductivity	transient analysis		measurement	
Provides precise measurements of heat generated by solar cells, offering a thorough assess- ment of thermal effects	Can determine the thermal con- ductivity of solar cell materials, essential for understanding heat dissipation mechanisms	Allows for both steady-state and transient thermal analysis, offering a comprehensive view of thermal behavior (Polo-Men- doza et al., 2023)	Experiments often involve specialized equipment and set- ups, making them more challenging and time-consuming to perform	Measurements are typically local- ized and may not capture tem- perature variations across the entire solar cell	Rapid temperature changes may not be captured adequately due to the heat accumulation and dissipation nature of calo- rimetry (Park et al., 2022)

Comprehensive data	Direct relevance	Applicability	Limited temperature control	Surface effects	Time-consuming
Techniques provide comprehensive data on the electrical response of solar cells under different thermal conditions (Zhao et al., 2020c)	Directly assess the impact of tem- perature on solar cell electrical character- istics, including effi- ciency, open-circuit voltage, short-circuit current, and fill factor (Zhao et al., 2020c)	Can be integrated into existing solar cell testing setups, making it a practical choice for research and development (Failed, 2023b)	Some experimental setups may have lim- ited control over tem- perature variations, affecting the accu- racy and repeatability of measurements	Focuses primarily on the electrical response and may not provide insights into localized tem- perature variations	Conducting experiments at multiple temperature points can be time-consuming (Abina et al., 2023)

 Table 11
 Advantages and limitations of temperature-dependent characterization

and parallel wiring, as highlighted in Table 18, is a critical consideration in solar cell installations. Series wiring can affect how individual cells heat up and cool down during operation. Specifically, series wiring may lead to higher operating temperatures in individual cells (Pásztory, 2021). This is a result of the cumulative effect where the current passing through each connected cell contributes to its temperature. The discussion underscores the importance of carefully selecting the wiring configuration based on the specific requirements of the solar energy system and the desired balance between efficiency and thermal considerations. Inverter efficiency, as indicated in Table 18, is a crucial factor influencing thermal effects on solar cells. Inverters play a central role in converting the direct current (DC) generated by solar cells into alternating current (AC) for use in homes or the grid. The efficiency of this conversion process is paramount, as less efficient inverters may produce more waste heat (Pásztory, 2021). The discussion highlights the need for selecting high-efficiency inverters to minimize the impact of waste heat on the overall temperature of the solar energy system. This becomes particularly relevant.

Table 19 succinctly presents the considerations associated with different tracking systems and their impact on solar cell temperature. This discussion provides insights into the role of tracking systems in influencing the thermal performance of solar cells, with a focus on the distinctions between single-axis and dual-axis tracking. The central point in Table 19 revolves around the choice between single-axis and dual-axis tracking systems. Single-axis tracking systems adjust the tilt of solar panels in one direction, typically east to west, to follow the sun's path across the sky. On the other hand, dual-axis tracking systems offer a more precise adjustment by altering both tilt and azimuth to track the sun more accurately (Sani et al., 2022). The discussion emphasizes that while tracking systems can enhance energy yield by optimizing sunlight exposure, they may also introduce additional thermal stress on solar cells, especially when in motion. The considerations outlined in Table 19 are crucial for system planners and operators. The decision between single-axis and dual-axis tracking involves a trade-off between increased energy generation and the potential introduction of additional thermal stress on solar cells. Single-axis tracking is generally less complex and may be more suitable for certain installations, whereas dual-axis tracking provides enhanced accuracy in following the sun's movement.

Mitigation strategies for thermal effects on solar cells

The adverse effects of temperature on solar cells are a well-known challenge in the field of photovoltaics. To maximize the efficiency and lifespan of solar energy systems, it's essential to implement effective mitigation strategies. In this section, we will explore various approaches to mitigate the negative impact of temperature on solar cells, including passive and active cooling techniques, as well as the use of advanced materials and designs to enhance thermal stability (Luo et al., 2020). Figure 9 provides a visual comparison of different cooling techniques for solar cells (Dwivedi et al., 2020). It shows passive cooling, which relies on natural processes, and active cooling, which involves mechanical systems. The figure highlights the advantages and limitations of each technique, helping engineers and researchers choose the most suitable cooling method for specific solar installations.

Strategies to mitigate adverse effects of temperature

Mitigating the adverse effects of temperature on solar cells involves employing various strategies. Passive cooling techniques aim to dissipate heat from solar cells without the need for active mechanical systems. They rely on natural processes, including radiative cooling using materials with high emissivity, natural convection facilitated by well-designed solar panels, and shading or elevation to reduce direct ground exposure (Akin et al., 2020; Dwivedi et al., 2020; Kazem et al., 2020). On the other hand, active cooling

Factors	Considerations
Temperature Extremes	Solar cells in extreme conditions (hot deserts or cold climates) may experience efficiency variations (Osma-Pinto & Ordóñez- Plata, 2019)
Seasonal Variations Cloud Cover	Winter cold can reduce efficiency in cold climates, while summer heat can lead to thermal losses (Salamah et al., 2022) Reduced sunlight during cloudy conditions affects both cell temperature and electricity generation efficiency (Weaver et al., 2022)

Table 12 Climate and weather conditions impacting solar cell temperature

 Table 13
 Geographic location impact on solar cell temperature

Factors	Considerations
Latitude	Closer proximity to the equator results in higher temperatures (Din et al., 2023)
Altitude	Higher altitudes tend to have lower average temperatures (Din et al., 2023)

 Table 14 Impact of installation angle and orientation on solar cell temperature

Factors	Considerations
Tilt Angle	Adjusting panel tilt based on the sun's posi- tion can minimize solar cell temperature, particularly in hot climates (Atsu et al., 2020)
Orientation	The orientation of panels (north–south, east–west) affects the sunlight received and, consequently, solar cell temperature (Atsu et al., 2020)

techniques utilize mechanical systems to actively remove excess heat. Forced convection involves using fans or blowers to enhance heat dissipation, especially effective in regions where natural convection is insufficient. Liquid cooling systems circulate a heat-transfer fluid through channels on the back of solar panels, absorbing heat and cooling before recirculation. Additionally, phase-change materials (PCMs) can be integrated into solar panel designs to regulate temperature by absorbing excess heat during the day and releasing it at night. These strategies collectively contribute to optimizing the efficiency and reliability of solar energy systems (Liu et al., 2021; He et al., 2020; Ravishankar et al., 2020; Xu et al., 2021). Table 20 distinguishes between passive and active cooling techniques. Passive cooling relies on natural convection, radiation, and other phenomena to dissipate heat, while active cooling involves the use of fans, liquid cooling, or other mechanical methods to actively remove heat from solar cells.

Advanced materials and designs to enhance thermal stability

Enhancing the thermal stability of solar cells involves the integration of advanced materials, improved designs, smart technologies, nanomaterials, and advanced manufacturing techniques (Li et al., 2020). Utilizing thermally conductive substrates like aluminum or copper helps spread and dissipate heat effectively, reducing localized hotspots. Thermal barrier coatings on solar panels minimize heat absorption and transfer, with reflective properties to reduce thermal load. Enhanced encapsulation materials with high thermal conductivity efficiently dissipate heat from the solar cells (Dwivedi et al., 2020; Tawalbeh et al., 2021). Optimizing solar cell designs includes the use of bifacial solar cells capturing sunlight from both sides to reduce absorbed heat. Back-side reflectors redirect unabsorbed sunlight, minimizing heat absorption. Advanced designs may incorporate selective emitter structures improving electrical performance at high temperatures (Aydin et al., 2019; Gupta et al., 2019). Integrating smart and adaptive technologies enhances thermal management. Embedded temperature sensors monitor

Table 15 Impact of solar cell material on thermal performance

Factors	Considerations
Material Bandgap	Bandgap influences photon absorption; materials with smaller bandgaps may be more susceptible to thermal losses (An et al., 2019)
Material Thermal Conductivity	Materials with higher thermal conductivity can better manage temperature variations (An et al., 2019)



Fig. 8 Solar cell efficiency across different band gap energies under various spectral distributions and power densities (Sze, 1981)

cell temperatures in real-time, adjusting cooling systems or shading devices as needed. Advanced tracking systems adjust panel orientation to optimize energy generation and reduce thermal stress (Hachicha et al., 2019). Nanomaterials contribute to thermal stability through thin nanocoatings controlling heat absorption and dissipation. Nanofluids, consisting of nanoparticles in a liquid, enhance the efficiency of liquid cooling systems (Chen & Park, 2020; Wang et al., 2020). Advanced manufacturing techniques further enhance thermal stability. Multi-junction solar cells with multiple semiconductor layers achieve higher efficiencies and are less susceptible to thermal losses. Thin-film solar cells, inherently less thermally sensitive, are suitable for a wider range of operating conditions (Ilse et al., 2019; Santhakumari & Sagar, 2019).

Case studies: influence of thermal effects on solar cell performance

To gain a deeper understanding of the impact of thermal effects on solar cell performance, it is instructive to examine real-world case studies across different geographic regions and climatic conditions. In this section, we present case studies that highlight the diverse challenges and solutions associated with thermal effects on solar cells, drawing upon relevant studies and data.

Case studies in various geographic regions and climatic conditions

Exploring case studies from diverse geographic regions reveals the varied impacts of climate on solar cell performance. In the scorching heat of Nevada, USA, where temperatures often exceed 100°F (37.8°C), solar cell efficiency faces challenges. The University of Nevada, Las Vegas, conducted a study highlighting the impact of high temperatures on photovoltaic systems. Actively cooled systems, incorporating fans and water cooling, outperformed passive systems during peak heat. However, passive systems with efficient natural convection still maintained acceptable performance (Devitt et al., 2020). In the Arctic conditions of Northern Norway, within the Arctic Circle, harsh winters with sub-zero temperatures affect solar cell efficiency. Researchers at the Norwegian University of Science and Technology discovered that utilizing bifacial solar panels, capturing light from both sides, enhanced energy generation during the low-light winter months, mitigating the adverse effects of extreme

 Table 16
 Influence of solar cell design on thermal effects

Factors	Considerations
Anti-Reflective Coatings	Coatings reduce sunlight absorption, lowering cell temperature (Sze, 1981)
Back-Side Reflectors	Reflectors redirect unabsorbed sunlight, potentially increasing cell temperature (Sze, 1981)
Cell Thickness	Thicker cells have higher thermal mass, impacting temperature changes and differences across the cell (Gupta et al., 2019)
Bypass Diodes	Diodes mitigate hotspots and thermal effects by allowing current to bypass overheating or shaded cells (Gupta et al., 2019)

Table 17	'Effect of	encapsulation a	nd packagin	g on solar ce	Il temperature
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Factors	Considerations
Encapsulation Materials	Materials must possess good thermal conductivity for effective heat dissipation
Ventilation and Cooling	Proper ventilation and cooling systems are essential for maintaining optimal temperatures (Yue et al., 2021)

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Table 18 Impact of electrical and wiring configuration on solar

Factors	Considerations	
Series vs. Parallel Wiring	The arrangement affects heating and cooling; series wiring can lead to higher operating temperatures in individual cells	
Inverter Efficiency	Inverter efficiency influences thermal effects; less efficient inverters may pro- duce more waste heat (Pásztory, 2021)	

cold (Berge et al., 2015). Moving to Malaysia, situated near the equator with high humidity and frequent rainfall, solar cell performance faces different challenges. While high temperatures are typical in tropical regions, humidity can lead to corrosion and electrical leakage. A study by Universiti Teknologi Malaysia emphasized the importance of using advanced encapsulation materials and regular maintenance to mitigate humidity-related

Table 10 Julius as of the days	
TABLE 19 Influence of tracking s	ystems on solar cell temperature
Factors	Considerations
Single-Axis vs. Dual-Axis Tracking	Tracking systems impact temperature stress; dual-axis systems may introduce additional stress (Sani et al., 2022)



Fig. 9 a Comparison of cooling techniques, b Passive radiative sky cooling and c Model of a P.V. panel with heat sink (Dwivedi et al., 2020)

issues, prolonging the lifespan of solar panels in humid climates (Wong et al., 2018).

Case studies: data and findings from relevant studies

Exploring relevant case studies sheds light on the diverse impacts of temperature on solar panel performance. In a study examining the impact of temperature on thin-film solar panels across various climates, researchers observed that while thin-film panels were less susceptible to thermal losses in extreme heat, their efficiency decreased compared to silicon panels in temperate regions. This emphasizes the need to carefully choose panel technology based on the specific climatic conditions of a region (Rahman et al., 2023). Saudi Arabia, known for its hot desert climate, presented unique challenges in a study by researchers from King Abdullah University of Science and Technology (KAUST). They found that extreme heat, coupled with dust accumulation on solar panels, significantly reduced solar cell efficiency. To address this, the researchers proposed an innovative self-cleaning

Table 20 Passive vs. active cooling techniques

Cooling technique	Description
Passive cooling	Relies on natu- ral processes for heat dis- sipation
Active cooling	Utilizes mechani- cal systems to remove heat

solar panel system with a hydrophobic coating and integrated microscale channels. This approach demonstrated promising results in maintaining panel performance in harsh desert environments (Rubaiee et al., 2021). A comprehensive study conducted by researchers from the University of California, Merced, focused on temperature-dependent performance modeling of solar panels across diverse climates. The study emphasized the importance of accurate modeling considering environmental factors, material properties, and panel design. By incorporating real-world data from various regions and climates, researchers could optimize solar panel designs and develop effective cooling strategies tailored to specific environmental conditions (Al-Housani et al., 2019). Table 21 illustrates how solar cell efficiency can vary in different climate zones. Desert regions experience high temperatures that reduce efficiency, while temperate climates offer more favorable conditions. Arctic regions may face efficiency challenges due to extreme cold, and tropical climates may contend with high humidity affecting performance.

Future trends and research directions: addressing thermal challenges in solar cells

As the world increasingly turns to solar energy as a sustainable power source, the need to address thermal challenges in solar cells becomes more critical. Researchers and innovators are continually exploring emerging technologies and research areas to enhance the efficiency and reliability of photovoltaic systems. In this section, we will discuss the future trends and research directions aimed at tackling the thermal challenges faced by solar cells, highlighting potential breakthroughs and innovations.

Emerging technologies and research areas

Ongoing research in emerging technologies focuses on advancing materials and cooling techniques to enhance the thermal stability of solar cells and improve overall performance. One avenue of research involves developing advanced materials tailored to withstand thermal stresses. Innovations include the exploration of thermal barrier coatings with reflective properties to reduce heat absorption and enhance dissipation (Al-Fartoos et al., 2023). Nanotechnology offers opportunities to engineer nanocoatings and nanofluids, providing enhanced thermal regulation when applied to solar cells. Additionally, the study of thermoelectric materials is underway, aiming to capture waste heat from solar cells and convert it into additional electricity, thereby increasing overall energy yield (Song et al., 2023). In the realm of cooling technologies, researchers are exploring microfluidic cooling systems with tiny channels within solar panels to circulate cooling fluids effectively (Liu et al., 2018). Phase-Change Materials (PCMs) with tailored phase-change temperatures are being investigated for their ability to store and release heat at specific thresholds, contributing to precise thermal regulation. Hybrid cooling systems, combining active and passive cooling strategies, are also being explored to optimize thermal management 146]. The integration of smart and adaptive technologies is gaining momentum. Machine learning and AI algorithms are being employed to analyze real-time data from temperature sensors and weather forecasts, optimizing solar panel operations. Bifacial solar panels, capturing sunlight from both sides, are becoming more prevalent to enhance energy generation and alleviate thermal effects. Dynamic shading and tracking systems are under development to adapt to changing environmental conditions, mitigating excessive sunlight exposure and minimizing thermal stress on panels (Riedel-Lyngskær et al., 2020; Johansson et al., 2022).

Potential breakthroughs and innovations

Quantum dots and perovskite solar cells are emerging as potential transformative technologies in the solar industry, offering promising solutions to thermal challenges. Quantum dots, semiconductor nanocrystals with unique optical and electronic properties, are being investigated for their potential impact. Researchers are exploring quantum-dot-based solar cells that can capture a broader spectrum of sunlight. This has the dual advantage of reducing heat absorption by the cell and enhancing overall efficiency (Chen & Zhao, 2020). Perovskite solar cells are highly efficient and demonstrate superior thermal stability. Ongoing research is dedicated to improving the scalability and long-term stability of perovskite solar

Table 21 Solar cell efficiency in different climates

Climate	Impact on solar cell efficiency
Desert	High temperatures reduce efficiency
Temperate	Moderate temperatures optimize efficiency
Arctic	Extremely cold temperatures may decrease efficiency
Tropical	High humidity can affect efficiency

cells, making them more viable for widespread commercial applications. These breakthroughs hold the promise of further advancing the efficiency and reliability of solar energy systems (Lim et al., 2022). Table 22 outlines potential breakthroughs in solar cell technology. Quantum dots and perovskite cells have shown promise in increasing efficiency. Transparent solar panels offer aesthetic integration, while space-based solar power eliminates atmospheric issues. Tandem cells combine materials for both efficiency and thermal management improvements. These innovations represent exciting directions in solar energy research.

Transparent solar panels, designed for integration into windows and building materials, present opportunities to enhance aesthetics and reduce heat absorption. Researchers are exploring materials such as organic photovoltaics and transparent conductive oxides to create these panels, capturing sunlight without inducing significant heat buildup. Building integration of transparent solar panels seamlessly incorporates them into architectural designs, offering an alternative to traditional opaque panels that may contribute to thermal issues on building surfaces. Figure 10 visually illustrates the architectural applications, showcasing solar panels integrated into rooftops and façades, emphasizing their aesthetic and functional potential for sustainable building practices and energy generation (Pulli et al., 2020). Figure 10 showcases the integration of solar panels into building designs. It demonstrates various architectural applications, such as solar panels integrated into rooftops and façades (Vasiliev et al., 2019). This visual representation emphasizes the aesthetic and functional potential of solar panels, contributing to sustainable building practices and energy generation.

Space-based solar power (SBSP) is a visionary concept involving the collection of solar energy in space and transmitting it to Earth using microwave or laser beams. While in theoretical research, SBSP could potentially address terrestrial solar panel thermal challenges by operating in a consistent temperature environment free from atmospheric effects and benefiting from continuous sunlight (Baum et al., 2022; Saha et al., 2015). Perovskite-silicon nologies, hold the potential to significantly enhance solar cell efficiency while addressing thermal issues. Tandem cells leverage the strengths of both technologies, optimizing materials to minimize thermal losses and enhance overall thermal stability (Akhil et al., 2021). The solar industry's increasing focus on sustainability includes recycling and repurposing solar panels. Advanced recycling techniques aim to recover valuable materials from end-of-life solar panels, reducing environmental impact and lowering the demand for new materials. Sustainable manufacturing methods are also under exploration to minimize energy consumption and thermal waste during panel production (Daniela-Abigail et al., 2022). In conclusion, addressing thermal challenges in solar cells is pivotal for the future of solar energy. Emerging technologies, from quantum dots to transparent panels, space-based solar power, tandem cells, and recycling methods, offer promising solutions. These innovations have the potential to reshape solar energy production, unlocking higher efficiency, greater reliability, and a more sustainable future for solar energy systems. Ongoing research in these areas is key to advancing the solar industry towards a greener and more efficient future.

Conclusion: addressing thermal effects for enhanced solar cell efficiency

In this comprehensive review, we have delved into the complex world of thermal effects on solar cells, exploring their mechanisms, impact, and various strategies for mitigation. As the world increasingly turns to solar energy as a key component of the renewable energy landscape, understanding and addressing thermal challenges in solar cells are of paramount importance. In this concluding section, we summarize the key findings and insights from the review, emphasize the significance of mitigating thermal effects for improving solar cell efficiency, and provide practical recommendations for researchers, engineers, and policymakers.

 Table 22
 Potential breakthroughs in solar cell technology

Breakthrough	Description
Quantum Dots	Quantum dots capture a wider spectrum of light
Perovskite Solar Cells	Perovskite cells offer high efficiency and thermal stability
Transparent Solar Panels	Transparent panels can be integrated into building materials
Space-Based Solar Power	Space-based solar power eliminates atmospheric effects
Tandem Solar Cells	Tandem cells combine materials for improved efficiency and thermal management



Fig. 10 Solar panel integration in buildings (Vasiliev et al., 2019)

Key findings and insights

In the course of this review, several noteworthy findings have surfaced. Thermal effects on solar cells emerge as a pervasive and intricate challenge, considering that solar panels contend with a broad spectrum of temperatures, significantly influencing their efficiency and durability. Elevated temperatures, a common factor, precipitate reduced solar cell efficiency by fostering electron-hole recombination, modifying the bandgap properties of materials, and introducing resistive losses. The exploration of various mitigation strategies has been integral. Passive and active cooling techniques, advanced materials, smart and adaptive technologies, and innovative designs have been examined to regulate temperature and enhance the overall thermal stability of solar panels. The advent of emerging technologies adds an exciting dimension. Quantum dots, perovskite solar cells, transparent panels, and space-based solar power showcase potential breakthroughs, promising to reshape the solar industry by effectively addressing thermal challenges and elevating efficiency. The growing emphasis on sustainability and recycling in solar panel manufacturing and end-of-life disposal is another key insight. Sustainable practices and recycling methods are gaining prominence, offering avenues to reduce the environmental impact and enhance the lifecycle management of solar panels.

Importance of understanding and addressing thermal effects

Understanding and addressing thermal effects on solar cells holds immense significance for various reasons. Firstly, it directly influences efficiency, a critical factor in optimizing energy generation within solar energy systems. A comprehensive approach to managing thermal challenges can result in efficiency gains, ultimately maximizing the energy yield of photovoltaic systems. Secondly, the longevity and reliability of solar panels, considered as long-term investments, hinge on effective thermal management. By mitigating thermal effects, the lifespan of solar panels can be extended, reducing maintenance costs and enhancing overall performance over the years. Economic viability is another crucial aspect. The efficiency of energy production and low operating costs are essential for the economic sustainability of solar energy. Addressing thermal effects directly contributes to cost-effectiveness, improving the return on investment for solar installations. Lastly, sustainability is a key driver behind the adoption of solar energy, contributing to the reduction of greenhouse gas emissions and environmental sustainability. Managing thermal effects aligns seamlessly with sustainability goals by ensuring the efficient utilization of solar resources, thereby reinforcing the role of solar energy in environmentally friendly energy solutions.

Practical recommendations

Practical recommendations for stakeholders in the solar energy sector involve a multifaceted approach. Researchers are encouraged to advance materials science by exploring advanced materials with enhanced thermal properties. Collaborative research, particularly interdisciplinary efforts, is essential for developing comprehensive solutions that address both electrical and thermal aspects of solar panels. Innovations in cooling technologies, such as microfluidic systems and phase-change materials, should be a focal point. Additionally, researchers should invest in modeling and simulation tools that accurately consider thermal effects in diverse environmental conditions. Engineers play a vital role in implementing effective cooling strategies tailored to specific environmental conditions. This includes the adoption of smart technologies, such as AI-driven tracking systems and dynamic shading devices, to optimize solar panel performance in realtime. Regular maintenance protocols, including cleaning to mitigate dust accumulation, and monitoring solar panel temperatures and performance, are crucial for early anomaly detection. Policymakers are urged to incentivize sustainable practices by creating policies that promote eco-friendly manufacturing processes for solar panels and support recycling programs to reduce environmental impact. Allocating resources to research and development in solar energy, with a specific focus on addressing thermal challenges and fostering innovation, is paramount. Furthermore, policymakers can accelerate the transition to renewable energy sources by encouraging solar adoption through favorable policies, including tax incentives, feed-in tariffs, and net metering. In conclusion, the future of solar energy is bright, but addressing thermal effects on solar cells is an essential component of unlocking its full potential. As we continue to advance in materials science, cooling technologies, and sustainable practices, we move closer to a world where solar energy is not only an efficient and reliable power source but also a cornerstone of a sustainable and environmentally conscious future. By understanding the complexities of thermal effects and embracing innovative solutions, we can harness the power of the sun to create a greener and more sustainable world for generations to come.

Supplementary Information

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Author contributions

The authors' contributions to this research project and manuscript are as follows: LMS contributed to the conceptualization, literature review, and data analysis, and played a significant role in writing and revising the manuscript. AAAA provided valuable insights into the theoretical aspects of thermal effects on solar cells and contributed to the critical analysis, particularly in the sections related to experimental methods and case studies, and contributed to the manuscript's writing and editing. WKAA contributed to the discussions on emerging technologies and research directions, as well as the potential breakthroughs in the field. AAHK played a crucial role in reviewing and editing the manuscript for clarity, coherence, and scientific rigor.

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Declarations

Ethics approval and consent to participate

Ethical approval was not required for this comprehensive review as it does not involve human subjects, animals, or personal data. All information and data used in this review are derived from publicly available sources, scientific literature, and previously published research studies.

Consent for publication

All authors have provided their consent for the publication of this research paper in Sustainable Energy Research.

Competing interests

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