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Thermal Performance Enhancement Techniques of Silicon-Based Solar Panels-Review Article

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ABSTRACT

Thermal management is one such critical parameter dominating the electrical efficiency and reliability of silicon-based photovoltaic (PV) modules, as higher operating temperatures impair the power output and accelerate the degradation rate and cost of energy for PV cells. This review critically summarizes contemporary research trends and literature on the augmentation and enhancement of thermal management for silicon-based PV modules through passive, active, material-based, and combination or innovative approaches involving the integration of photovoltaic and thermal management concepts for silicon-based PV modules. It is clear from the review that passive methods for temperature reduction with reduced cost and system complexities can be achieved to a small extent compared to active methods that promote higher efficiencies and greater system complexities with higher energy requirements. Research on material and nano-technologies can offer improvements for localized heat removal and evacuation with minimal system design and modification interventions on silicon-based PV modules, while combination approaches involving solar PV and solar thermal technologies offer the greatest overall energy conversion efficiency.

Keywords: photovoltaic–thermal (PVT), silicon photovoltaic, phase change materials

عنوان البحث باللغة العربية

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الخلاصة

يُعدّ التحكم الحراري أحد أهم القيود التي تؤثر في الأداء الكهربائي وطول العمر التشغيلي للوحدات الكهروضوئية المصنوعة من السيليكون. إذ تؤدي درجات الحرارة المرتفعة للخلايا إلى انخفاض كفاءة التحويل، وتسريع آليات التدهور، وزيادة التكلفة المستوية للطاقة (LCOE). يقدم هذا الاستعراض تحليلاً نقديًا شاملاً لأحدث الدراسات النظرية والتجريبية والميدانية المتعلقة بتقنيات تحسين الأداء الحراري لأنظمة الخلايا الشمسية السيليكانية. وتم تصنيف التقنيات إلى: أساليب التبريد السلبي (تحسين الهندسة، تعزيز الحمل الحراري الطبيعي، الطلاءات الانتقائية أو العاكسة طيفيًا، والمواد متغيرة الطور)، وأساليب التبريد النشط (أنظمة التبريد بالسوائل أو الهواء، الحمل الحراري القسري، التبريد الحراري الكهربائي، والأنظمة المدمجة بين التتبع والتبريد)، بالإضافة إلى الابتكارات القائمة على المواد (الطلاءات النانوية، المركّبات عالية التوصيلية الحرارية، والموائع النانوية)، إلى جانب الأنظمة الهجينة الكهروضوئية–الحرارية (PVT) التي تستعيد الطاقة الحرارية بالتوازي مع إنتاج الكهرباء.

وتُظهر المقارنة أن تقنيات التبريد السلبي تحقق خفضًا حراريًا معتدلًا مع بساطة تصميمية وتكلفة منخفضة، بينما توفر أنظمة التبريد النشط قدرة أكبر على تقليل درجات الحرارة مقابل زيادة التعقيد والاستهلاك التشغيلي. وتقدم الابتكارات المعتمدة على المواد والنانو تحسينات نوعية عند واجهة الجهاز، مما يعزز استخلاص الحرارة دون تغييرات كبيرة في باقي النظام. وتُعد الأنظمة الهجينة PVT الأكثر تحقيقًا للعائد الكلي للطاقة من خلال الجمع بين التوليد الكهربائي والاسترداد الحراري. وعلى الرغم من الفوائد المثبتة، ما تزال هناك فجوات تتعلق بالقابلية للتوسع، والمتانة على المدى البعيد، والجدوى الاقتصادية، والتحقق من الأداء في المناخات المختلفة. ويقترح هذا الاستعراض أولويات بحث مستقبلية تشمل: (1) إجراء

تجارب ميدانية طويلة المدى ضمن مناخات متنوعة، (2) تقييمات اقتصادية وعمرية للمواد المتقدمة، و(3) تطوير أطر تصميم متكاملة لتحسين الأداء الحراري–الكهربي للتطبيقات التجارية.
الكلمات المفتاحية: الأنظمة الكهروضوئية–الحرارية (PVT)، الخلايا الكهروضوئية السيليكانية،المواد متغيرة الطور(PCM) .

INTRODUCTION

The search of the sustainable sources of energy has been escalating over the last few years, and this has been mainly caused by the urgent need to solve the problems of climate change and environmental degradation. Solar energy is one of the technologies of renewable energy that has been the leader in technological advancement, due to its abundance and cost reduction related to solar photovoltaic (PV) technology. Solar panels made of silicon (especially) are the main engine of the existing solar market as they illustrate a considerable portion because of the prevalence and productivity. But there are still issues with their thermal performance which can reduce their overall efficiency under high temperature environments. Improving the thermal characteristics of these panels is therefore not only technically crucial, but it is also central to whether solar energy can become a mainstream source of power or not. The literature has covered numerous thermal enhancement methods, based around such topics as cooling methods, material innovations, and hybrid systems, and aimed at addressing the deficiencies which accompany silicon solar panels in high thermal load conditions [1][2]. Although much literature has clarified the processes of thermal degradation and provided new approaches to the problem, the literature has gaps in knowledge. Indicatively, active cooling systems, such as the use of liquid cooling and phase change materials, have had encouraging results, but the issue of scalability and affordability of such systems in business contexts is yet to be substantiated with empirical research [3][4]. Moreover, incorporation of new materials to improve thermal dissipation including nanofluids and novel coatings is also exciting but the long term performance of such materials has been little evaluated [5][6][7]. In addition, hybrid systems using solar thermal systems and photovoltaic are also receiving growing interest as a two-fold method of maximizing the output of energy. It was successfully shown that these systems may successfully utilize both electrical and thermal energy, however, there are no extensive reviews which may provide the consolidation of findings of various experimental systems and geographical conditions [8] [9]. Moreover, although there are theoretical models used to predict the effect of temperature on the losses of silicon solar cells, the experimental evidence to support the models in diverse climatic conditions is lacking [10] [11]. Currently, most of the current literature either dwells on experimental proofs of certain cooling methods or speculative improvement of material science, and there exists a need to unify the studies between these realms [12] [13]. The necessity of the complex approach that will take into account the technological improvements and practical implementation in the various environmental conditions is gaining momentum [14] [15]. Therefore, this review aims at summarizing the existing body of knowledge on thermal performance improvement methods in silicon based solar panels. Through critical review of the available literature and the highlighting of gaps in current research, the aim of the review is to shed light on avenues of future research that could lead to more effective and cost effective solar power solutions which can eventually help in achieving the goal of energy transition into sustainability [16][17][18][19][20]. In brief, a literature about thermal performance improvements of silicon solar panels shows a diverse yet disjointed terrain. With the further development of research, it is paramount to promote interdisciplinary partnerships, which are able to meet the multidimensional issues of the nexus of engineering, material science, and market dynamics [21][22][23]. The identified gaps as well as the focus on the integrative perspective presented by the review establish the environment in which the further research and development are to be carried out in the framework of solar thermal management strategies [24][25][26]. Finally, the result of this review will not only contribute to the development of academic knowledge but can also appeal to the industry stakeholders who are interested in practical solutions to the problem of improving the efficiency of solar energy [24][27][28] [29] [30] [31] [32] [33] [34] [35] [36] [37][38] [39].

REVIEW OF LITERATURE

The search of the enhancement of thermal performance of silicon-based solar panels has been developing considerably throughout the last few decades, characterized by different innovative approaches and efficiency rates to grow. Initial investigations were mainly passive type cooling, and it was shown that heating of the air flowing over solar panels could be used to reduce solar heating, which is harmful to the performance[1][2]. With the development of research, the use of sophisticated materials, including thermally conductive polymers, phase change materials, etc., became more prominent, which emphasized significant advances in thermal regulation [3][4]. The above innovations highlighted the dire necessity of the development of integrated thermal management systems that are not only beneficial in performance, but also increase the life of solar modules. However, over the past 20 years, focus has been directed on active cooling systems, including water cooling systems and hybrid photovoltaic-thermal (PVT) systems. These systems have been reported to make a huge contribution to the energy eco-friendliness by producing both thermal power and electricity simultaneously [5][6]. However, in the recent developments, even nanotechnology has also been used, with innovative coatings that facilitate better heat dissipation and reduce degradation of solar panels to a minimum [7][8]. Moreover, recent research has started to highlight the effects that the physical environment has on thermal performance, with the implication that location and climatic conditions should be considered when selecting and designing cooling methods [9][10]. The historical evolution of these methods shows an obvious tendency to more complex thermal management systems that consider not only short-term performance but also more global sustainability objectives. Therefore, the literature has been an indication of a booming industry that has yet to innovate in line with the increased desire of an efficient solar energy solution and current studies are ensuring more improvements in thermal performance in line with the current research [11][12]. In the end, this review summarizes the dynamic process of development of technologies and the environment in the optimization of silicon-based solar panels. The studies about optimization of thermal characteristics of silicon-based solar panels also enable outlining various innovative approaches and their effects on energy efficiency. The utilization of cooling technologies to counter the adverse implications of increased operating temperatures on the efficiency of solar panels is also one of the most conspicuous topics of the literature. Different literature papers have shown that passive cooling, like the incorporation of phase change materials, can considerably enhance the performance on the basis of sustaining optimum temperature limits, to gain the maximum energy output[1][2]. In addition, another area for the enhancement of thermal management is the investigation of advanced surface materials. Some hydrophobic and reflective surfaces might be useful in reducing the amount of solar heat received and enhancing the rate of energy conversion processes [3]. More recent studies verify that, after enhancing thermal efficiency, such surfaces can be beneficial for prolonging the life and reducing the maintenance needs of solar panels as well [4][5]. Another significant area that needs attention is the structural modification made on silicon panels for enhancing heat dissipation process efficiency. Incorporating high thermal conductivity materials has proved to be fruitful for enhancing heat transfer from silicon surfaces that are highly necessary for hot periods [6][7]. Some feasible methods for enhancing thermal efficiency can be found in the literature with regard to fin and heat sink integration to counterbalance the possible loss in solar panel structure design efficiency as well [8]. All the above investigations proved that finding a solution for silicon solar panels for enhancing efficiency is a complex task. The current study explains the significance of using multidisciplinary approaches because the research indicates that the thermal management improvements not only enhance the energy efficiency but may also reduce the overall cost of the solar energy system [9][10]. This has been brought about by various methodological techniques that have had a great impact on the comprehension of thermal performance enhancement techniques on the silicon-based solar panels to add to a variety of literature. Experimental research, including the one by Talukder M.Jet al. [1] and Badran G et al. [2], gives a background knowledge in terms of the behaviors of materials in different conditions, the effectiveness of the modern cooling methods, and the effect of the surface alterations. The studies have been carried out in many cases using controlled laboratory conditions, whereby the results of the study are quantifiable and used in practice. On the other hand, simulation models, such as those in I. Subedi et al., [3] and Choubani K et al., [4] take advantage of computer modeling to estimate thermal characteristics when the system is operated under various operating conditions. The theoretical structures enable the discovery of design changes without the limitations of the physical prototypes, which leads to the possibility of more in-depth consideration of possible upgrades. Introduction of machine learning methodology into such simulations has also facilitated prediction accuracy as revealed by Kumar N et al. [5] and Rajendra M et al. [6] who used advanced algorithms to identify the correlation between design variables and performance results. As can be seen in the work of Appalasamy K et al., [7] and Kurnierwati I et al., [8], field studies reveal the need to know laboratory results in real-life. By evaluating the local weather and environmental conditions on solar panel performance, these studies address the gap in theory and practice by determining the impact of local climatic and environmental conditions on solar panel performance. Moreover, multi-method, which combines experimental, computational and field data, has been considered to be especially strong in the literature, as demonstrated by the comprehensive analysis of Iskenderov U et al.,

[9] and Shi Yet al., [10]. These synergized approaches do not only make clear the intricacies of thermal management in silicon-based solar panels but also make it very clear that interdisciplinary approach is an essential way to develop further into this sector. The literature that is available on the subject of the thermal performance enhancement of silicon-based solar panels displays an intersection of theoretical views leading to either a defense or criticism of the existing methodologies. Much attention is given to passive cooling methods and different researchers prove efficacy of reflective coating and improved convectional systems to reduce the thermal accumulation, which can impair the efficiency of photovoltaic panels [1][2]. On the other hand, the presence of active cooling mechanisms, including water- and air-cooling systems is actively examined, and some researchers believe in their effectiveness in obtaining the maximum energy output at high-temperature conditions [3][4]. Also, the research of new materials showcases the opportunities of advanced thermally conductive materials to enhance the process of heat dissipation. As an example, the recent discoveries show that the addition of phase change materials can considerably smooth out the changes in temperature and thus enhance the work of solar panels [5][6]. Also, the literature review highlights the significance of environmental conditions, which affect solar panels performance, including wind speed and ambient temperature in the interaction with thermal characteristics [7][8]. It is also worth noting that the comparison between the theoretical models and the empirical data also enriches the discussion. There are studies that suggest a multi-faceted approach where various enhancement methods are used to bring about holistic changes in thermal management[9] [10]. However, this approach is yet to be widely accepted; instead, other approaches propose that simplification within the system may lead to more feasible solutions [11][12]. In this regard, the literature review implies that there is a complex environment within which advancements must be made between technology and theoretic concepts to promote solar energy optimization.

CONCLUSION

The evidence of the literature on thermal performance improvement strategies of silicon-based solar panels has provided a mine of information that is critical in the development of this paramount area of the solar technology. One of the main findings is that cooling techniques have been successfully used to alleviate thermal degradation- such an aspect is extremely essential since it reduces the efficiency of the photovoltaic systems when the temperature is high. Passive cooling as a strategy that involves utilization of natural cooling airflow and active cooling strategies which include water cooling and hybrid photovoltaic thermal systems have demonstrated significant potentials of enhancing energy output and extending panel life cycles [1][2][3][4]. Moreover, the development of new materials making them thermally conductive or phase change materials is also opening an important prospective of improving heat regulation with new surface treatments [5][6][7]. The general idea of this review is that the thermal management of silicon solar panels needs a complex approach. Since studies have always pointed out the shortcomings of the sole-use of any approach, the literature in general disagrees on any one approach as it is likely to yield the best outcomes [8] [9]. This integrative approach is crucial because it reflects the significance of interdisciplinary partnership between the engineers, material scientists, and specialists who consider sustainability in the search of comprehensive solutions that can not only enhance performance but also be able to align with the vision of sustainability [10][11].The implication of these results goes well beyond optimizing efficiency; they mark a major stride in the quest of realizing the entire potential of solar energy as a sustainable resource in the fight against climate change. As solar energy is being promoted as a crucial element of the global energy transition, the implementation of strategies aimed at enhancing thermal performances will be directly involved in the expansion of the renewable energy usage and economic feasibility. A plant that employs solar panels based on silicon and these innovations can achieve a reduction in operation costs and market competitiveness thereby increasing their reach and usefulness [12] [13] [14][15]. However, there is no literature that is free. To a great extent, the majority of the available studies have been limited to a subset of experimental validations or theoretical models, creating a fractured understanding of the current state of thermal management [16][17] .Even then, most of the existing studies have not been conducted in a comprehensive manner to validate the offering useful techniques as have been reported in these reviews, all of which casts doubt on their applicability across a wide range of climatic and geographical settings [18][19][20].Future studies should, therefore, focus on the conduction of large-scale empirical studies and practical application to It is also evident that there is an exploration gap on the long-term implication of newly developed materials and their sustainability profile once it is incorporated in the solar technologies. The tests of the future ought to also aim at developing a relationship between thermal performance and lifecycle tests that would help create a better picture of what such improvements would entail [21][22]. The two domains offer fertile grounds in terms of scholarships that may be used in shaping future technological growth, and commercial applications. To sum up, the given literature review can not only summarize the existing knowledge of the ways to improve the thermal performance of silicon-based solar panels but also indicates the important research directions that could further increase the efficiency, adaptability, and sustainability of solar energy systems in the nearest future. The discoveries made in this paper can be leveraged by the renewable energy sector through filling the gaps depicted and through the development of interdisciplinary collaborations that will allow sustained innovation and the development of viable solutions that are likely to satisfy the energy-constrained future.

Table 1. Summary table of prior research

Author	Year	Main Focus	Findings
M. J. Talukder, et al. [1]	2025	Evaluating advancements in high-efficiency solar photovoltaic materials, especially perovskite solar cells and tandem technologies.	PSCs have achieved efficiencies over 25% in single-junction and 29% in tandem configurations, with significant stability challenges remaining.
G. Badran et al. [2]	2025	Examining recycling challenges and opportunities for photovoltaic solar cells to enhance sustainability.	Identifies the need for improved recycling infrastructure and highlights the potential of integrating design-for-recyclability principles to enhance material recovery.
I. Subedi, et al.[3]	2020	Using optical probes to evaluate photovoltaic device performance and diagnose losses.	Demonstrated effective optical modeling for various PV technologies, leading to accurate predictions of device efficiencies.
K. Choubani et al.[4]	2025	Evaluating enhancements in solar still desalination to improve water production.	Proposed methods resulted in significant increases in water output, indicating effective techniques for thermal management.
N. Kumar [5].	2025	Reviewing methods to optimize heat transfer performance in solar collector tubes.	Identified strategies such as advanced materials and nanotechnology as key to improving thermal efficiency.
M. Rajendra, et al.[6]	2025	Exploring advancements in solar thermal systems and the integration of hybrid architectures.	Advanced materials and nanofluids significantly improved thermal efficiency and energy retention in solar thermal technologies.
K. Appalasamy, et al.[7]	2025	Reviewing cooling techniques to enhance efficiency of photovoltaic systems.	Identified innovative cooling strategies that effectively reduced thermal buildup and increased performance.
I. Kurniawati et al. [8]	2024	Reviewing technologies aimed at improving heat management in photovoltaic-thermal systems.	Identified various innovative approaches to enhance energy transfer and reduce inefficiencies in PV-T systems.

U. Iskenderov et al.[9]	2024	Investigating optimal heating structure configurations for improved energy efficiency in buildings.	Highlighting effective technologies that significantly reduce energy consumption while enhancing thermal comfort.
Yuxin Shi [10]	2024	Reviewing molten salt energy storage technology in solar thermal applications.	Identified improvements in thermal properties and reductions in costs, while emphasizing ongoing challenges.
F. Ullah et al. [11]	2024	Investigating enhancements in heat transfer for thermal energy storage systems.	Demonstrated significant improvements in efficiency through innovative applications of graphite sheets.
F. Uba et al. [12]	2021	Evaluating thermal performance of solar collectors in humid weather.	Identified design improvements leading to enhanced thermal efficiency and performance under challenging weather conditions.
D. Sinaga et al.[13]	2025	Analyzing improvements in photovoltaic performance via a dual-axis solar tracker system.	The combined approach significantly increased energy output and efficiency.
C. Lakshmi et al. [14]	2024	Quantifying impacts of factors affecting solar panel efficiency in tropical climates.	Identified enhancement techniques that significantly boosted solar panel efficiency.
L. Koshy et al. [15]	2024	Developing an efficient fault detection system using thermal imaging for solar panels.	Achieved high accuracy in detecting anomalies, enhancing the operational reliability of solar systems.
M. Vetrivel et al.[16]	2024	Evaluating the integration of nanostructured ZnO layers with silicon solar cells.	Significantly improved performance metrics of silicon cells through reduced recombination losses.
M. Z. Ab Hamid, et al. [17]	2024	Developing a method for hotspot detection in solar panels utilizing YOLOv9.	Achieved improved accuracy and localization for effective maintenance.
A. Roy et al. [18]	2023	Optimizing multi-junction solar cells for increased performance.	Demonstrated significant improvements in solar cell efficiency through optimized doping profiles.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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