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Advanced Solar Energy Systems: Current State and Optimization Strategies – A Comprehensive Review

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Abstract *The growing global demand for energy, along with the urgent need to combat climate change, has accelerated the transition from fossil fuels to renewable energy sources, with solar energy emerging as a significant alternative. This systematic review evaluates the current state of advanced solar energy systems and explores optimization methods aimed at enhancing their energy, economic, and environmental performance. It consolidates recent developments in solar technologies alongside optimization methodologies. Additionally, it examines how climatic conditions, geometric configurations, and operational parameters influence system efficiency. The review provides a comprehensive analysis of various optimization strategies, including methods based on the laws of thermodynamics, control strategies, statistical approaches, machine learning techniques, and genetic programming, all of which are essential for improving energy conversion efficiency while minimizing total system costs. By systematically reviewing the existing literature, this study identifies significant knowledge gaps and provides insights into future directions for optimizing solar energy systems. The findings contribute to ongoing efforts to enhance solar energy technologies and promote their widespread adoption within sustainable energy frameworks.*

Keywords *solar energy systems, advanced solar technologies, optimization methods, energy efficiency*

1. INTRODUCTION

The extensive energy potential of the sun, coupled with the worldwide increase in the demand for solar energy, poses significant challenges for solar technologies and stimulates the development of innovative engineering solutions.

Advanced methods have been developed to optimize system efficiency, yet challenges persist due to solar energy's inherent variability. Solar power output is highly dependent on external factors, making energy optimization models that account for these variables essential for improving energy production efficiency. Addressing these issues and adopting optimal technical solutions is critical for reliable integration of solar energy into power systems.

This paper investigates the current state of advanced solar energy systems, providing a comprehensive review of cutting-edge technologies and optimization methods – specifically, an analysis of existing research in this field. The primary objectives of applying optimization methods to solar systems are to reduce dependence on fossil fuels, increase solar energy conversion efficiency, lower costs and emissions, and enhance system reliability.

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2. CURRENT STATE AND RECENT DEVELOPMENTS OF ADVANCED TECHNOLOGIES IN SOLAR ENERGY SYSTEMS

Various active technologies are employed to convert solar energy into different energy carriers for subsequent use [1].

Flat-plate photovoltaic (PV) technologies are widely adopted due to their simplicity in energy production. Crystalline silicon has contributed to the development of stable solar cells with efficiencies up to 20%. In thin-film solar cell technologies, the average conversion efficiency ranges between 7-10% [1].

In concentrated solar power (CSP) technologies, a working fluid is heated by concentrated sunlight and then used for electricity generation or thermal energy storage [1]. In parabolic trough systems, the overall solar thermal power plant efficiency is the product of collector efficiency, array efficiency, and steam cycle efficiency. Studies report collector efficiency can reach values as high as 75%. For central receiver systems with heliostats, heat transfer fluids may include water, molten salt, liquid sodium, or air [1, 2]. The development of novel heat transfer fluids is crucial for enhancing system efficiency. Compact linear Fresnel reflectors offer the advantage of using flat mirrors, which are significantly cheaper than parabolic mirrors, while allowing higher reflector density within the same area – enabling greater utilization of available solar irradiance [1]. Parabolic dish systems demonstrate the highest efficiency among CSP technologies, reaching up to 30% [1].

The solar technology industry still possesses significant potential for development and innovation. This creates opportunities for further advancements, optimization, and development of new technologies in solar energy. Innovations in materials, cell design, and manufacturing methods enable engineers to achieve substantial efficiency improvements while simultaneously reducing solar energy production costs.

Perovskite solar cells utilize a hybrid organic-inorganic halide material based on lead or tin as the active light-absorption layer. Recent advances in perovskite cells have shown remarkable efficiency improvement, increasing from 3.8% in 2009 to 25.7% in 2021 [3].

Tandem solar cells combine different PV technologies, such as silicon and perovskites, to maximize light absorption and improve conversion efficiency.

Transparent solar panels are designed to integrate PV cells into windows, displays, and other transparent surfaces without compromising functionality or aesthetics.

Nanostructured materials provide increased surface area and shorter charge carrier diffusion lengths, leading to enhanced efficiency. These are typically fabricated using advanced nanotechnology processes.

The absorption coefficient of amorphous silicon is one order of magnitude higher than crystalline silicon in the 400-700 [nm] wavelength range [4]. Consequently, less silicon material is required to absorb solar radiation, reducing material costs.

The kesterite solar cell composition consists of copper-zinc-tin sulfide (CZTS), designed as an absorber layer for thin-film solar cells exhibiting p-type conductivity [4].

Numerous studies have been conducted to minimize cell reflectance through anti-reflective coatings (ARC). Currently, over 70% of commercially available PV panels are equipped with ARC on either the cover glass or the solar cell itself. The coatings aim to bring the refractive index as close as possible to 1.00 without compromising light transmittance [5].

In areas with significant soil pollution, annual energy losses due to soiling can reach up to 50%. These losses necessitate the development of panel cleaning mechanisms through two approaches: hydrophobic and hydrophilic coatings [5].

Bifacial solar modules generate electricity from both direct sunlight and reflected/diffuse light. This technology can increase the total energy production capacity of PV systems by utilizing available sunlight more efficiently.

Advanced battery technologies for solar energy storage are being researched and developed, with lithium-ion batteries currently dominating the market due to their high energy density, efficiency, and declining costs. Optimization strategies involve charging batteries during low electricity price periods and discharging during peak pricing periods, thereby improving cost savings.

Single-axis and dual-axis solar tracking systems can increase electricity production by approximately one-third, with some sources suggesting up to 40% gains in certain regions compared to fixed-tilt modules [3].

Advances in solar technology have led to the development of rotating PV panel designs where proximity sensors play a key role in real-time orientation adjustment to maximize energy output [6].

Authors in [7] propose a system called IrSATA (Inclined N-S Axis with Relatively E-W Tracking Absorbers) that incorporates relative sun-tracking to improve efficiency while maintaining a compact design. By adjusting to solar angles, IrSATA operates longer than IFA (Integrated Fixed Array), increasing daily solar energy absorption. Numerical analysis using EnergyPlus demonstrates that IrSATA can absorb up to 20% more solar energy than IFA on clear days.

The optimized cleaning and cooling system in [8] increases energy production by 8.7% through dust accumulation reduction and maintaining panel temperature below 30 [°C], thereby improving overall system efficiency. The system demonstrates a positive net present value, making it an economically viable solution for utility-scale solar technologies. Maintaining solar cell temperature within permissible limits is crucial for ensuring optimal performance and efficiency.

Study [9] utilizes the latent heat of a cooling device to maintain PV panel temperatures near ambient levels. Experimental results were compared with a simulated cell-cooler model using computational fluid dynamics (CFD) software. Heat transfer analysis reveals that increasing fin count (from 5 to 15) enhances thermal dissipation, leading to improved temperature regulation and increased solar cell efficiency.

Building-integrated photovoltaics (BIPV) eliminate additional mounting system costs, improving the economic viability throughout the system's lifecycle.

Floating solar arrays benefit from water-induced cooling, resulting in higher efficiency. Although costs remain 10-20% higher compared to land-based installations, the installed capacity reached 3 [GW] by 2020 [10].

3. OVERVIEW OF OPTIMIZATION METHODS FOR SOLAR ENERGY SYSTEMS

The reliability of solar energy systems is significantly influenced by meteorological parameters. Consequently, optimization methods play a crucial role in enhancing both the reliability and efficiency of PV systems. Addressing this requires developing advanced methodologies to solve complex optimization problems in PV systems. Optimization approaches are fundamentally multi-criteria based [11], incorporating:

- Meteorological data,
- Load forecasting,
- Model accuracy,
- Specification diversity,
- Methodological simplicity,
- Implementation feasibility.

The subsequent analysis provides a thorough examination of the optimization strategies and models that have been established in solar energy systems, derived from a comprehensive evaluation of existing literature.

Module temperature substantially impacts PV system operation by altering conversion efficiency and power output. This temperature is governed by: ambient temperature, cloud cover index and wind velocity. PV module efficiency variations result from combined effects of solar irradiance intensity, ambient temperature, solar elevation angle and local weather conditions.

The performance evaluation of PV module orientations under real-world conditions reveals important insights. Reference [12] conducted a comprehensive comparison of horizontal, vertical, and optimally tilted monocrystalline PV modules exposed to actual meteorological conditions over a full annual cycle. The study found that vertically oriented modules achieved the highest efficiency at 10.95%, followed by horizontal modules at 10.6%, while counterintuitively, modules at their theoretically optimal tilt angle showed the lowest performance at just 10.2% efficiency. This surprising result suggests that real-world environmental factors may complicate the benefits of optimal tilt angles in certain geographic locations.

Environmental degradation effects on PV performance have been extensively quantified in recent research. Study [13] carefully measured the efficiency reduction caused by natural airborne particulate deposition on panel surfaces, establishing a clear 0.4% monthly efficiency decrease when panels remain unmaintained in outdoor environments. More dramatically, experimental work [14] demonstrated extreme energy production reductions of 92.11% from uncontrolled dust accumulation, highlighting the critical importance of regular cleaning protocols, particularly in arid or industrial environments where particulate matter concentrations are elevated. Research [15] revealed that various environmental factors significantly affect module performance, with findings emphasizing that periodic maintenance is essential to mitigate soiling effects and maintain optimal energy output. This is particularly crucial for large-scale installations where even minor efficiency losses translate to substantial economic impacts over the system's operational lifetime. Advanced modeling approaches are providing new insights into solar thermal system optimization.

Authors in [16] employed sophisticated dynamic modeling techniques for flat-plate collectors, utilizing both explicit and implicit numerical methods combined with energy and exergy analysis methodologies. The research yielded several key findings: thermal gains showed marked increases during summer months, thermal output demonstrated direct proportionality to mass flow rate, and the heat removal factor emerged as a critical parameter determining overall system performance. These insights are proving valuable for the design of next-generation solar thermal systems with enhanced efficiency characteristics.

Study [17] focuses on optimizing solar energy utilization in distributed systems through machine learning techniques. The developed model ensures balanced energy storage utilization – neither overused (which would incur unnecessary costs) nor underused (which would lead to energy waste). The research demonstrates that implementing KNN (K-Nearest Neighbors) based machine learning for energy management in PV systems can reduce operational costs by 39% across various energy management strategies. However, the high cost of lithium-ion batteries currently limits large-scale implementation, requiring further cost reductions before energy storage becomes economically viable for utility-scale applications.

Reference [18] presents an innovative technical solution for solar collectors, investigating the application of genetic programming to model daily energy fluctuations. With a maximum average percentage error of just 14.6%, the results demonstrate genetic programming's strong potential for solar system optimization. The authors suggest that further improvements could be achieved by incorporating larger datasets and developing comprehensive universal functions that integrate all relevant parameters.

The selection of optimal locations for solar farms requires balancing competing economic, environmental, and technical criteria, making it a complex spatial optimization problem. Reference [19] proposes a multi-criteria optimization approach using an enhanced NSGA-II (Non-dominated Sorting Genetic Algorithm II) to evaluate six potential solar farm sites. The multi-objective optimization (MOO) identifies a Pareto front of solutions, enabling stakeholders to balance competing factors including solar irradiance levels, proximity to power grid infrastructure, urban planning considerations, topographical constraints. Results demonstrate that MOO techniques prove particularly effective for solar farm planning where conflicting spatial criteria complicate decision-making. This approach facilitates environmentally and socially responsible site selection while aligning with sustainable development goals.

Research [20] examines the efficiency of static and dynamic PV module models with single-axis solar tracking. The aim is to determine the optimal model for solar energy absorption and its conversion into electrical energy. The tracking systems utilize IoT (Internet of Things) technology. Results show that the solar tracking system, while being simple and cost-effective, can also increase electricity production compared to stationary systems. Real-time data analysis, remote access, and automated reporting enabled by the IoT-based performance monitoring system improve the performance, efficiency, and maintenance of solar systems.

Similar to [20], reference [21] investigates the optimization of solar PV field layouts using both fixed and single-axis tracking collectors to maximize annual energy output. A shading model was developed to optimize the spacing between rows and collector height, concluding that the distance must balance geometric constraints with energy yield benefits. Single-axis tracking systems with east-west oriented collectors outperform north-south oriented systems by generating 3.2% more annual energy, attributed to better alignment with the sun's path. However, both tracking systems significantly outperform fixed collectors in energy yield, highlighting the value of dynamic orientation adjustments. Temperature increase further impacts performance, reducing PV efficiency by 16.9% in north-south tracking systems and 17.46% in east-west tracking systems. These losses emphasize the need for integrated thermal management strategies in PV systems.

Study [22] investigates the optimization of tilt angles for solar collectors across six different climate zones to maximize solar radiation absorption. A key contribution of this research is the development of a simplified method for estimating the monthly average daily global solar radiation on tilted surfaces, which forms the basis for calculating monthly, seasonal, and annual optimal tilt angles. Monthly optimization provides the greatest energy yield benefits. Seasonal optimization reduces adjustment frequency while maintaining high efficiency, whereas annual optimization, with tilt angles close to the local latitude, offers a cost-effective solution with low maintenance requirements. However, the practicality of fixed annual tilt angles makes them the preferred choice in many scenarios, particularly in regions with limited resources for frequent maintenance.

Similar to [22], study [23] investigates the optimization of tilt angles for PV panels, emphasizing the interdependence between solar radiation models, temperature effects, and regional climate conditions to maximize energy output. Through an analysis of five cities, the research compares isotropic and anisotropic solar radiation models, demonstrating the superiority of anisotropic approaches such as the HDKR model. This model accounts for both circumsolar and diffuse solar radiation, improving annual energy yield estimates by 3.5-9% compared to isotropic methods, particularly in winter when diffuse radiation is significant. The tilt angle optimization reveals that fixed annual angles close to the cities' latitude establish an optimal balance between energy output and maintenance costs. Ambient temperature emerges as a critical factor, significantly reducing PV efficiency in warmer regions.

Using 2D numerical models and 3D Monte Carlo ray-tracing simulations, study [24] evaluates how geometric parameter adjustments in concentrated photovoltaic-thermal (CPV-T) solar collectors affect annual energy performance. The findings show that even minor geometric modifications contribute substantially to efficiency gains. The research also compares asymmetric and symmetric reflector designs, revealing trade-offs in seasonal performance that enable customization based on local climate conditions and energy consumption patterns.

Authors in [25] examine the thermal performance of a fixed flat-plate solar collector featuring a selective Sn-Al_2O_3 absorber with gravity-driven water flow, representing a sustainable alternative to conventional pump-dependent systems. The Sn-Al_2O_3 layer enhances solar absorption while minimizing radiative heat losses. The system's thermal efficiency was analyzed through a triple-iterative algorithm integrating solar angles, optical properties, and heat transfer coefficients. A Simple Linear Regression model correlates solar irradiance with thermal power output, enabling performance prediction with determination coefficients exceeding 90%. Performance validation identified critical thresholds, including a 770 [W/m^2] solar irradiance level above which thermal power increases linearly, providing practical insights for collector operational optimization.

In contrast to the flat-plate collector absorber optimization in [25], study [26] investigates the design and optimization of a parabolic dish system integrated with a spiral-wound thermal absorber. The absorber is engineered to maximize heat absorption while ensuring uniform thermal flux distribution. These geometric optimizations were validated through SolidWorks simulations, revealing stable energy efficiency of approximately 65% across input temperatures of 10-70 [°C] with only 0.07 [bar] pressure drop. Exergetic efficiency emerged as a key performance indicator, increasing from 4% at 10 [°C] to 15% at 70 [°C] input temperatures, highlighting the system's suitability for high-temperature applications where energy quality is prioritized.

Reference [27] investigates performance enhancement of solar air heaters through fin redesign in flat-plate solar collectors, addressing limitations of traditional hollow-fin heat transfer designs. The proposed spiral-fin collector incorporates blades and a central cylindrical structure to enable crosswise and longitudinal airflow, increasing turbulence. Numerical simulations show the spiral design generates secondary vortices that disrupt thermal boundary layers, achieving 65.2% thermal collection efficiency – significantly surpassing conventional flat-plate collectors (37.8%) and cylindrical fin collectors (58.6%). The dual airflow paths and secondary vortices ensure uniform heat distribution, making it suitable for building heating and agricultural drying applications.

Additionally, the study [28] presents an innovative design for a solar still that integrates phase-change material (PCM) energy storage along with fins. The investigation explores three variations of the still: (1) a conventional solar still (CSS) equipped with fins on the water side, (2) a CSS featuring fins on the water side and an unfinned PCM unit, and (3) a CSS that includes fins on both the water side and the PCM side. Paraffin wax is utilized as the thermal storage medium, which captures excess solar energy during the day and releases it at night. The findings indicate efficiency enhancements of 32% with fins alone, 46% with PCM in a finned reservoir, and 56% with fins on the PCM unit. When compared to traditional CSS, the modified systems exhibit productivity increases of 17.54% and 55.69%, respectively. The integration of fins and PCM results in a 2.5-fold increase in nighttime productivity, significantly boosting the thermal efficiency of the solar still.

Study [29] establishes the fundamental principles of energy, entropy, exergy, and endoreversible models in solar energy systems. These models simplify the explanation of the entropy generation minimization (EGM) method. Performance analysis of PV systems based on the first and second laws of thermodynamics is essential for identifying potential improvement areas – specifically locating entropy generation zones and applying appropriate minimization techniques.

The objectives of entropy generation minimization are to reduce energy losses, improve efficiency, and achieve environmental and energy benefits through various EGM strategies. The approach also prioritizes future research directions focusing on advanced EGM model development, EGM integration in new technologies, and experimental validation of EGM strategies to confirm their effectiveness [30].

In [31] the authors conducted a comparative analysis between the efficiency of a theoretical non-isothermal solar collector model and the efficiency obtained through measurements of a physical solar collector model. The collector, operating at a constant temperature, T_c, under steady-state conditions, absorbs solar radiation, which is partially transformed into useful energy while some is dissipated into the environment. This study employs the principles of endoreversible thermodynamics, where the energy from the incident radiation on the collector is denoted as q^*. A fraction of this energy is absorbed and conveyed by the working fluid, another fraction contributes to the internal energy of the collector, and the remaining energy is lost to the surroundings. The findings indicate a general trend of enhanced collector efficiency attributed to diminished irreversibility in the processes examined. The analysis yielded optimal operational parameters for the collector, including the ideal operating temperature, the intensity of useful heat, and the optimal flow rate of the working fluid.

Similar to the research conducted in [31], study [32] also focuses on flat-plate solar collectors as the subject of analysis. The researchers in [32] adopt a multidisciplinary approach that integrates thermodynamics, heat and mass transfer, and fluid mechanics principles. A detailed numerical analysis compares the thermodynamic performance of three distinct flat-plate solar collector designs using computational fluid dynamics (CFD) and entropy generation rate analysis. The investigated geometries include a conventional parallel-pipe configuration, and two zigzag-pipe configurations (Type A and Type B). The study aims to identify which model demonstrates optimal thermal performance with minimal irreversibility by calculating entropy generation from heat transfer, fluid viscosity, and thermal losses across various volumetric flow rates. Applying the second law of thermodynamics, the work emphasizes entropy generation minimization (EGM) as a critical method for improving energy conversion efficiency in solar collectors. Through comprehensive CFD modeling and simulations, the authors reveal how geometric modifications affect: heat transfer rates, pressure drops, and entropy generation. Type B collectors outperform both conventional and Type A designs in heat absorption capacity, evidenced by higher output temperatures across all tested flow rates. However, this enhancement comes with increased entropy generation due to enhanced heat transfer, fluid viscous effects, and particularly thermal losses – resulting from the expanded surface area and complex flow paths. The conclusion demonstrates that while zigzag

configurations improve thermal performance, they also introduce greater irreversibilities, necessitating careful optimization to balance energy gains against entropy generation for effective system design.
Similar to previous cases, [31, 32], study [33] presents a detailed investigation on the optimization of a flat-plate solar collector model using the entropy generation minimization method. The main objective of the research is to design a solar collector that minimizes system irreversibilities by reducing entropy generation due to heat transfer and airflow – a combination rarely considered in previous studies. What distinguishes this case from previous ones is that the collector is modeled as a finned heat exchanger, with parameters such as fin number, fin thickness, fin height, and airflow velocity being varied to analyze their effect on the dimensionless entropy generation number. The rate of entropy generation change consists of three components: the change in system entropy, the change in entropy due to heat transfer, and the change in entropy due to mass flow. The analysis incorporates dimensionless variables using the Particle Swarm Optimization (PSO) algorithm to determine the optimal set of model parameters that minimize entropy generation. Simulation results show that the number of fins and airflow velocity are the most influential factors. Although increasing the number of fins or their dimensions can improve thermal performance, it also increases entropy generation. Thus, optimization requires a balance where collector efficiency is improved without significantly increasing entropy generation, achieving thermodynamic optimization.

4. CONCLUSIONS AND FURTHER CONSIDERATIONS

Based on the conducted research regarding the current state of advanced solar systems and their optimization models, it can be concluded that each method for optimizing the energy performance of solar systems represents a complex and multidisciplinary approach. This requires the integration of multiple factors and the examination of each factor individually, as well as their combined effects, to enable proper optimization that would contribute to significantly improved efficiency and sustainability of solar energy systems. Table 1 presents a summary of key optimization strategies for solar energy systems considered in this review.
Through detailed analysis of various methods and technologies, a notable gap has been observed in research combining multiple optimization strategies for solar systems. The correct combination of hybrid optimization methods presents a challenging and complex task, potentially leading to computational difficulties and even reduced efficiency if the combination is not properly implemented.
In nearly all reviewed studies, particularly emphasized in [15], [16], [21], [22], [23], temperature emerges as the most influential parameter affecting the energy characteristics of solar cells. Increased temperatures reduce efficiency, necessitating careful balancing between module surface operating temperature and incoming solar irradiance. Additional challenges include dust and soiling deposits, which can block portions of sunlight and further decrease efficiency. These factors underscore the need for deeper investigations into optimization method performance under varying environmental conditions.
The implementation of adaptive IoT techniques – including automatic cooling, self-cleaning mechanisms, and solar tracking, as demonstrated in [20], proves equally effective for performance enhancement. Furthermore, both machine learning and genetic programming are being actively employed as efficient solar system optimization methods, with results validated by [17] and [18].
Multi-criteria approaches remain essential for developing comprehensive solar system optimization methodologies. However, formulating objective functions that incorporate multiple criteria with numerous parameters and constraints constitutes a non-trivial challenge, as evidenced by research [19].
Optimization methods for geometric parameters aim to extract maximum power from solar modules under variable weather conditions. However, implementing advanced solar tracking technologies also presents challenges, as solar irradiance intensity varies depending on time, location, and season.
Analysis of the entropy generation minimization (EGM) method applied to solar systems, particularly flat-plate solar collectors as investigated in [31], [32] and [33], reveals this technique as one of the newer approaches in

solar system optimization. The research itself opens new pathways for developing advanced solar technologies based on this principle. Current literature lacks studies that develop comprehensive mathematical models of solar modules capable of identifying entropy generation resulting from the influence of most climatic factors, expressing these relationships through appropriate mathematical formulations, and applying the EGM method to optimize system operation through geometric parameter adjustments. Consequently, new opportunities emerge for future research focused on addressing these challenges through application of the EGM methodology.

Table 1. Summary of Key Optimization Strategies for Solar Energy Systems

Optimization method	Main objectives and achievements	Limitations and research gaps	Key studies
Optimization Approaches for Primary Parameters and System Variables	Optimization of solar irradiance, temperatures, mass flow rates and other operational parameters	Limited to specific climate conditions and ambient temperature impact studies lack economic analysis	[12-16]
Machine Learning	Optimizing system performance by using KNN algorithm	High costs limit large-scale implementation	[17]
Genetic Programming	Evolutionary algorithm used for modeling a complex system	A lack of universal functions which integrate all relevant parameters	[18]
Multi-Objective Optimization	Balancing competing criteria by using NSGA-II algorithm	Limited to specific location – Maputo, Mozambique	[19]
Internet of Things	Real-time tracking and monitoring of PV systems	No evaluation of dual-axis sun tracking systems	[20]
Geometric Optimization	Optimization of geometric parameters such as tilt angles, elevation and implementation of sun tracking systems	The results are climate-dependent, especially on the ambient temperature as the most influential parameter	[21-24]
Absorber Optimization Techniques	Optimization of the properties of the thermal absorber by implementing different materials and designs	High material costs and manufacturing complexity	[25, 26]
Optimization Methods Using Different Fin Designs	Optimization of heat transfer by applying different fin geometries	Limited temperature ranges	[27, 28]
Entropy Generation Minimization	Thermodynamic optimization to reduce irreversibility and increase useful energy	A lack of climate-inclusive entropy models that mathematically link weather impacts to efficiency losses and guide geometric optimization by using EGM	[31-33]
Ångström-Prescott Model	Comprehensive estimation of solar radiation at daily/monthly/annual scales	Limited to specific location as it is validated only for Athens, Greece	[34]
Nanofluid Integration	Optimization of heat transfer by using nanoparticles	High production costs	[35, 36]

Despite existing advanced solar technologies and developed systems, there remains a lack of economic models to support these technologies, representing one of the key challenges associated with upgrading solar systems.

Further research on optimization of solar systems can not only contribute to increasing the efficiency of solar energy utilization, but can also provide cost-effective energy supply, which would result in significant growth in capacity and production of solar systems. The implementation of advanced optimization methods in solar systems can help achieve sustainable development in utilizing solar energy, in terms of clean energy, emission reduction and economic development. This is also confirmed by the latest research in the field of solar systems, such as [34], where a comprehensive statistical analysis of Ångström-Prescott advanced solar models for solar radiation estimation was conducted, identifying the most accurate models at daily, monthly and annual level and selection of the optimal model.

Furthermore, [35] and [36] examine the improvement of solar energy conversion efficiency in solar collectors through integration of nanofluids to increase absorption of solar radiation, improve energy performance, and increase long-term sustainability.

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