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MODELING SOLAR COLLECTORS: A REVIEW OF MODERN METHODS TO IMPROVE ENERGY CONVERSION EFFICIENCY UNDER CHANGING CLIMATIC CONDITIONS

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ABSTRACT

Efficiency and reliability in solar energy systems are largely influenced by the development of solar collector technologies and methodologies adopted for performance modeling under variable climatic conditions. This paper reviews recent approaches to modeling solar collectors, with a primary emphasis on the integration of solar tracking systems with advanced computational techniques such as artificial intelligence and hybrid models. The review highlights the use of long short-term memory (LSTM) models, neural networks, and AI-driven optimizations for enhancing energy conversion efficiency. It also provides an overview of the contributions of computational fluid dynamics (CFD) and thermodynamic models to the structural and thermal performance of solar collectors, mainly parabolic trough collectors (PTCs) and systems utilizing nanofluids as working mediums. Various case studies demonstrate the significant impacts of these modeling methods on improving efficiency and adapting to real-time environmental changes. The review concludes with recommendations for future work in integrating artificial intelligence (AI), hybrid model development, new material explorations, and long-term field studies to refine and enhance solar collector performance. These advancements are expected to contribute significantly to the future of solar energy, fostering sustainable and efficient energy solutions.

Keywords: Solar collectors, LSTM, Neural networks, Computational Fluid Dynamics, Solar tracking systems.

1.0 INTRODUCTION

In this regard, solar energy plays an important role in meeting the growing global demand for energy and minimizes adverse environmental impacts from the utilization of fossil fuel. The main technology used in the conversion of solar energy into thermal or electrical energy is the solar collector; hence, it assumes a major role in the entire process of energy conversion. These collectors are designed differently, and their efficiency depends on the working fluid and various operational parameters [1].

During recent years, great efforts have been developed in enhancing the thermal and optical performance of solar collectors, mainly in the domain of low-temperature applications. It aims at maximizing energy conversion efficiency due to changes within environmental and meteorological conditions for variable solar irradiance intensity and ambient temperature variations [2].

The dynamic character of the climatic conditions, with big variations in sun radiation and temperature, is quite a challenge for the solar energy system, since the function of solar collectors directly depends on these changes in sunlight and temperature. In view of this fact, new advanced models have been developed, aiming at optimum operation of solar collectors even under unfavorable conditions [3].

Solar trackers are an important emerging innovation for adjusting the position of the collector in tandem with the sun's movement, thus increasing captured energy, especially in areas of high climatic variability [4]. This review, therefore, intends to give a critical overview of the modern methodologies applied in modeling solar collectors, biased toward the integration of solar collectors with tracking systems for coping with ever-changing climatic conditions to realize maximum energy output. The article reviews recent works on modeling solar collectors and presents an advanced model to contribute to the quest for continued improvement in solar energy efficiency in various environmental regimes. Modern approaches are discussed more in detail in this paper of the state-of-the-art in modeling solar collectors, especially in association with their implementation with solar tracking systems. An important aspect in increasing the energy harvest of photovoltaic systems is solar tracking systems, as these extend the ability of the collector to trace the path of the sun. Considering this, the current available models will then be critically assessed regarding the changes in climatic conditions and limitations in this connection [4].

Besides, this literature review will develop and introduce a state-of-art model that integrates adaptive maximum power point tracking based on Long Short-Term Memory (LSTM) deep learning neural networks for solar photovoltaic tracking systems, in pursuit of upgrading the conversion efficiency of energy while dynamically responding to real climatic changes by optimizing the position of the solar collector to capture the highest possible energy. Energy conversion rates, system reliability, and adaptability to other climatic scenarios will be integrated into the model with some key performance indicators. [3].

2.0 LITERATURE REVIEW

2.1 Advancements in Solar Collector Technologies for Energy Efficiency

Solar collectors are crucial parts of renewable energy systems that provide an efficient interface between solar radiation and the conversion either to thermal or electrical processes. Flat plate collectors, parabolic trough collectors, and evacuated tube collectors are the main solar collector types that fall within specific design characteristics and application areas [5].

1. **Flat Plate Collectors:** Among the most used solar collector designs, the flat-plate collectors consist of an insulated box with a transparent cover and an absorber plate [6]. Due to their relatively simple design and cost-effectiveness, these are among the most common of the collectors currently used for systems to produce domestic hot water and space heating. However, their performance is many times compromised by low heat concentration and dependence upon ambient temperature [7].
2. **Parabolic Trough Collectors:** These are collectors that focus sunlight onto a receiver tube at the focal point of parabolically curved mirrors. Parabolic trough systems can therefore achieve much higher temperatures than flat plate collectors, which makes them useful in industrial applications such as the generation of steam and in very large solar power plants. Efficiency depends greatly on precise sun-tracking mechanisms to maximize capture [8].
3. **Evacuated Tube Collectors:** These collectors are made up of parallel rows of glass tubes, each containing an absorber tube enclosed in a vacuum. The vacuum is used as the insulating medium and greatly reduces the heat loss; that makes evacuated tube collectors quite effective in colder regions or under overcast conditions [9]. The temperature range that it operates within is higher than the flat-plate collectors can achieve, making them good-to-go both for domestic and industrial uses [10].

Table 1 explains comparison between them.

Table 1. Comparative Analysis of Solar Collector Types

Collector Type	Advantages	Limitations	Applications
Flat Plate Collectors	Simple, cost-effective, widely available	Low heat concentration, ambient-dependent	Domestic water heating, space heating
Parabolic Trough Collectors Evacuated Tube Collectors	High-temperature capability, efficient sun-tracking	High initial cost, complex maintenance	Industrial steam generation, solar power plants
Evacuated Tube Collectors	Minimal heat loss, effective in colder climates	Higher cost, limited market availability	Domestic and industrial heating systems

2.2 Challenges in Energy Conversion Efficiency

Despite the progress made in solar collector design, several challenges continue to affect their energy conversion efficiency. Key factors that influence the performance of solar collectors include [11]:

1. **Solar Irradiation and Climatic Conditions:** Solar collectors are individually very sensitive to changes in radiation and temperature, which could make quite remarkable changes in performance. In variable climatic conditions-cloudy or cold weather, for example-the efficiency of the energy conversion process falls owing to low solar irradiance and high heat losses [7].
2. **Heat Loss Mechanisms:** Heat loss in the solar collector occurs via conduction, convection, and radiation. While evacuated tube collectors minimize conductive and convective losses due to their vacuum design, flat plate and parabolic trough collectors bear a maximum of heat losses, especially at night or during low solar irradiation [10].
3. **Working Fluids and Heat Transfer:** Selection of the working fluid is the most critical factor in solar collectors, since it could make a difference in the overall efficiency of energy conversion [12]. Fluents with high thermal conductivity, while they promote better heat exchange, may have higher heat losses. Solar collector efficiency also depends on the effectiveness of the working fluid in standing extreme temperatures without degradation [8].
4. **Design and Material Limitations:** In the design of the collector, performance is directly linked with the geometries of the absorber and the selected material for the transparent cover [13]. Poor selection of materials may further lead to issues such as high reflectivity of the cover, insufficient insulation, and degradation of absorber surfaces that result in lower energy conversion efficiency.

2.3 Solar Panel Tracking Systems: An Overview

Solar tracking systems are vital to harness maximum efficiency from solar panels in such a way that they continuously modify the angle of their position to track the path of the sun through a day. In general, two major kinds of solar tracking systems prevail: single-axis and dual-axis tracking systems, each with different advantages in energy capture versus system complexity [14].

1. **Single-Axis Tracking Systems:** While in single-axis tracking systems, the solar panels are mounted on a structure that enables rotation about one axis, either horizontal yielding an east-west movement or vertical, yielding north-south movement. On grounds of cost and design simplicity, single axis tracking systems are preferable. Single-axis trackers will act most effectively in boosting energy capture during morning and afternoon hours when the angle of the sun is also changing quicker [15]. While such systems had the potential to increase the effectiveness of solar collection by up to 25% over that of static systems, their capacity to address seasonal variations in the sun's position is limited.
2. **Dual-Axis Tracking Systems:** Dual-axis tracking systems are designed such that solar panels can move along horizontal and vertical axes for complete freedom of movement in following the path of the sun. These systems are more complex, more expensive, and offer higher efficiency gains, especially in regions that have significant seasonal variations in solar irradiance. These dual-axis trackers can increase the capture of solar energy by up to 40% compared to the static system and are hence ideal in areas where maximization of energy output is crucial [16]. Their ability to adjust to both daily and seasonal sun movements make them more suitable in areas with fluctuating climatic conditions [6].

The comparison of both single- and dual-axes tracking system is available in Table 2.

Table 2. Comparison on Single-Axis and Dual-Axis Tracking Systems

Feature	Single-Axis Tracking System	Dual-Axis Tracking System
Movement Axis	Rotates on one axis (horizontal or vertical)	Rotates on both horizontal and vertical axes
Complexity	Simpler design and construction	More complex design and construction
Cost	Less expensive	More expensive
Energy Capture Efficiency	Increases energy capture by up to 25% compared to static systems	Increases energy capture by up to 40% compared to static systems

Feature	Single-Axis Tracking System	Dual-Axis Tracking System
Best Performance Timing	Most effective during morning and afternoon hours	Effective throughout the day and year, especially with seasonal changes
Suitability for Seasonal Variations	Limited ability to adjust for seasonal changes	Adjusts to both daily and seasonal sun movements
Ideal Usage	Preferable for cost-effective solutions and simple applications	Ideal for maximizing energy output in areas with fluctuating climates or significant seasonal variations
Efficiency Gain	Moderate gain in energy capture (25%)	High gain in energy capture (40%)
Climate Suitability	Works well in regions with consistent sunlight	Best suited for regions with significant seasonal changes in sunlight

2.4 Advantages of Solar Tracking

Their power is in the fact that they maximize the exposure of solar panels to sunlight, greatly increasing the energy capture compared to any static solar installation. In a fixed system, the solar panels are held at a fixed angle within the installation and usually optimized for maximum energy at only one point during the day, typically noon. This means that since their angles are fixed, the energy capture is considerably lowered during other times of the day when the position of the sun changes from that one point [17].

1. **Increased Energy Capture:** Solar trackers, both single-axis and dual-axis, immensely enhance energy capture since the panels are always oriented towards the sun. This increased exposure can result in an overall energy yield improvement of up to 25% and 40% for single- and dual-axis systems, respectively, compared to fixed installations [16]. This is most advantageous in the case of huge solar farms where even minute gains in efficiency have a tremendous effect on total energy production [18].
2. **Adaptability to Climatic Conditions:** Probably one of the most important advantages of solar tracking systems is their ability to adapt to fluctuating climatic conditions. In places where there is considerable cloud cover or variable sunlight due to shifting seasons, static solar systems capture energy less consistently. Solar trackers can optimize energy capture by adjusting the panel orientation even to capture diffuse sunlight, thereby improving energy efficiency in less-than-ideal weather conditions [6]. This adaptability therefore renders the tracking systems very important, particularly for those regions that have unpredictable weather or variable changes in weather.
3. **Economic Efficiency:** Whereas tracking systems are more expensive initially, the complication on mechanisms for tracking and control would also require increased investment; nevertheless, higher capture might also mean higher economic returns in the long term. In large-scale solar installations, the energy gains provided by tracking systems can significantly offset the initial costs, hence making such tracking systems economically viable in areas with high solar potential [16].

2.5 Methods of Modeling Solar Collectors

Traditional modeling approaches in solar collectors have generally been performed by mathematical and analytical techniques such as energy balance equations, thermodynamic models, and finite element analysis. These models try to simulate the dynamic processes within a solar collector by calculating the heat transfer rates, energy losses, and efficiencies of solar collectors for several environmental conditions [19].

1. **Energy Balance Equations:** Energy balance models represent a solar collector as a system of energy inputs, which include solar radiation, and outputs, which include thermal or electrical energy and associated heat losses. Hence, energy balance equations solve the task of equating the incoming solar radiation with energy losses by conduction, convection, and radiation to get an estimate for efficiency and temperature distribution across the collector. These equations are the very basis for understanding thermal behavior in solar collectors and further form the base for more complex models [20].
2. **Thermodynamic Models:** Thermodynamic models take into consideration the working fluids and properties of materials in solar collectors. Such models incorporate laws of thermodynamics in determining various parameters, including heat transfer coefficients, thermal efficiency, and operating temperatures. In applications where heat losses must be maintained at minimum values, such as in

parabolic troughs and solar towers, thermodynamic models have proved useful for optimizing the performance of solar collectors at high temperatures [21].

3. **Finite Element Analysis (FEA):** FEA is used to investigate and predict the structural and thermal performances of solar collectors under a wide range of loadings and environmental conditions. In principle, such a method allows for the accurate prediction of the distribution of stresses, temperature gradients, and possible failure points by subdividing the structure into smaller elements and the subsequent solving of the relevant governing equations for each of the elements. This is particularly useful in large-scale solar collectors, such as parabolic trough collectors, whose structural stability is crucial during operation [21].

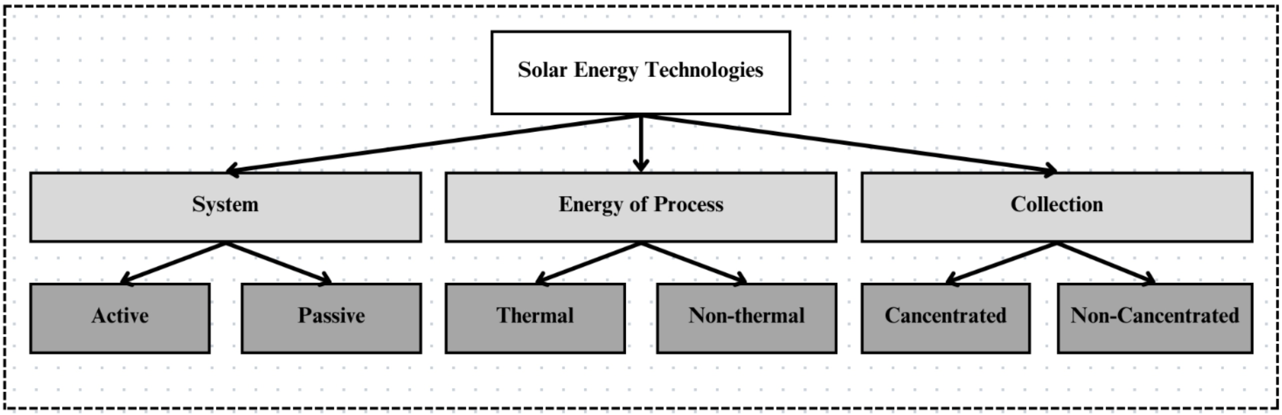

Figure 1. Classification of solar energy technologies [20].

Figure 1 represents the categorization of solar energy technologies, showing major categories of solar systems, energy processes, and collection methods. This figure develops the distinction between active and passive systems and between concentrated and non-concentrated collectors, providing a more complete overview of the different solar energy technologies [22].

2.5.1 Computational Fluid Dynamics (CFD)

The ability of CFD to model the fluid flow in the system and the process of heat transfer is central to the attempts at improving the design and performance of solar collectors. CFD resolves the governing equations of fluid dynamics and heat transfer by using numerical methods, thus providing very substantial detail on the behavior of the working fluids and air flows around the collector [23].

This is particularly useful in CFD for optimization purposes in the design of solar collectors by predicting temperature distributions, pressure drops, and heat exchange rates across complex geometries. As an example, by using CFD, in parabolic trough collectors (PTCs) it is possible to simulate the interaction of the heat transfer fluid with the absorber tube, enabling the modification of the process of exchanging heat with great accuracy [20].

Figure 2 shows some of the characteristics of different solar concentrating technologies: parabolic dish, linear Fresnel reflector, and solar tower. Table 3 shows the capacity, efficiency, and temperature of various systems to provide a general view of their comparative performance characteristics.

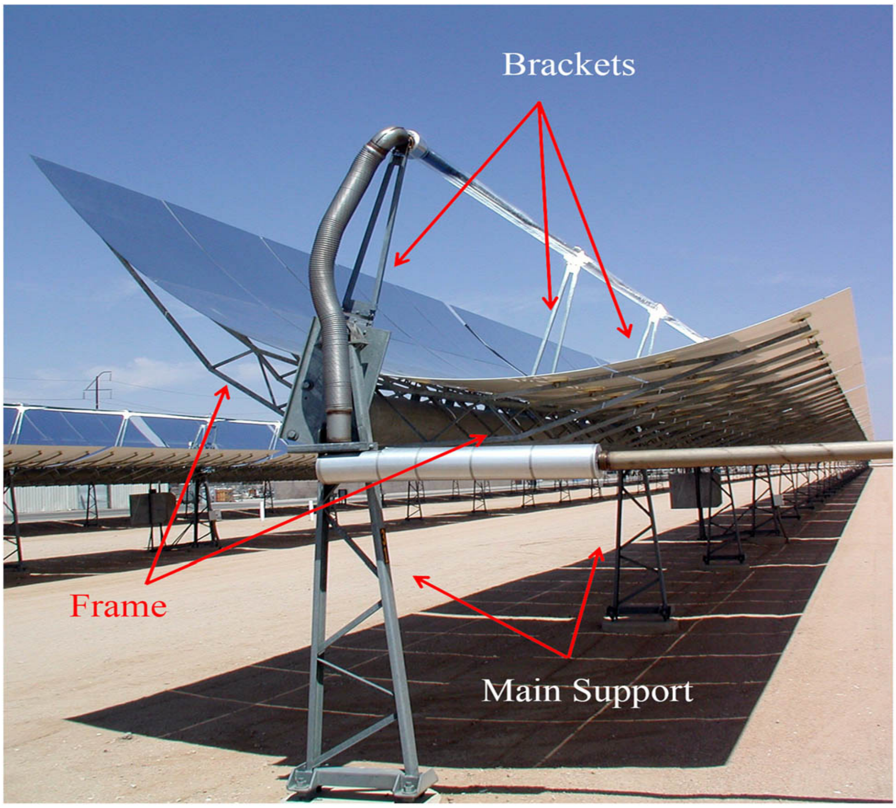

Figure 2. Structural division of a PTC [20]

Table 1. Comparison of solar concentrating technologies [20].

Category	Parabolic Trough	Solar Tower	Linear Fresnel	Parabolic Dish
Typical capacity (MW)	10–300	10–200	10–200	0.01–0.025
Maturity	Commercially proven	Commercially proven	Recent commercial project	Demonstration projects
Technology development risk	Low	Medium	Medium	Medium
Operating temperature (°C)	350–400	250–565	250–350	550–750
Plant peak efficiency (%)	14–20	23–35	18	30
Annual solar to electricity efficiency (%)	11–16	7–20	13	12–25
Annual capacity factor (%)	25–28 (no TES)	55 (10 h TES)	22–24	25–28
Concentration factor	10–80	>1,000	>60	Up to 10,000
Receiver/absorber	Absorber attached to collector, moves with collector, complex design	External surface or cavity receiver, fixed	Fixed absorber, no evacuation secondary reflector	Absorber attached to collector, moves with collector
Storage system	Indirect two-tank molten salt at 380°C (dT = 100 K)	Direct two-tank molten salt at 550°C (dT = 300 K)	Short-term pressurized steam storage (<10 min)	No storage for Stirling dish, chemical storage under development
Hybridization	Yes, and direct	Yes	Yes, direct (steam boiler)	Not planned

Category	Parabolic Trough	Solar Tower	Linear Fresnel	Parabolic Dish
Grid stability	Medium to high (TES or hybridization)	High (large TES)	Medium (back-up firing possible)	Low
Cycle	Superheated Rankine steam cycle	Superheated Rankine steam cycle	Saturated Rankine steam cycle	Stirling
Steam conditions (°C/bar)	380–540/100	540/100–160	260/50	n.a.
Maximum slope of solar field (%)	<2	<4	<4	10 or more
Water requirement (m^3/MWh)	3 (wet cooling)	2–3 (wet cooling)	3 (wet cooling)	0.05–0.1 (mirror washing)
Application type	On-grid	On-grid	On-grid	On-grid/off-grid
Suitability for air cooling	Good	Good	Low	Best
Storage with molten salt	Commercially available	Commercially available	Possible, but not proven	Possible but not proven

2.5.2 Empirical and Semi-Empirical Models

Empirical and semi-empirical models, on the other hand, depend on experimental data and observation in developing correlations that predict performances of solar collectors. These models are usually elicited from laboratory experiments or field data when the system's underlying physics is too complex and thus cannot be described correctly with purely theoretical models.

1. **Empirical Models:** Empirical models are based on the direct measurement of the performance of a system operating under varying conditions. This type of model is often used to predict the realistic performance of solar collectors and has been very useful in making quick and efficient performance estimations in practical applications.
2. **Semi-Empirical Models:** Semi-empirical models, on the other hand, are based on a blend of theoretical principles and experimental data, which may then be used to make more general performance predictions. Essentially, these kinds of models are used to develop solar collectors for specific applications-such as solar water heating or industrial process heat [21].

Various elements constituting the structural frame of the parabolic trough collector. A main support and brackets hold the main structure frame. This figure helps to understand in advance the complexity of PTCs and their structural stability and their accurate alignment will be very important regarding the energy they capture as shown in Figure 2.

2.6 Modeling of Solar Collectors with Solar Tracking Systems

Solar collectors must integrate solar tracking systems to ensure that the collector would have better performance by tracking the trajectory of the sun. In integrating tracking systems, mathematical and computational models showing real-time behavior of the collector are used because it continuously changes its position toward the tracking of the Sun. Using tracking systems will adjust the orientation of the collector continuously for a better capture of solar radiation throughout the day.

Most of these models implement solar tracking by calculating the most appropriate angles for capturing energy at any given geographical location, daytime, and atmospheric condition. The computational models, although their working is on predictive algorithms, help in the tracking of the path and position of the sun to keep the collector at the best position.

Location of the end sensors in a solar tracking system. Figure 3 shows that the sensors are in contribution to the precise measurement of the position of the sun and feed into the tracking algorithm for real-time adjustments. [24] as shown in Figure 3.

Figure 3. Location of end sensors of the system [10]

2.6.1 Hybrid Models

Hybrid modeling approaches that encapsulate several methodologies, such as thermodynamic and computational models, have been successful in capturing the added complexities brought about by solar tracking systems. For instance, the thermodynamic model can be used in the estimation of heat transfer and energy efficiency, while the computational model, such as Computational Fluid Dynamics or Finite Element Analysis, is used in simulating the physical behavior of the solar collector-especially the time-varying climatic conditions.

This represents an added importance of CFD models in solar tracking systems because they enable the observation of fluid flow and heat transfer behavior after the movement of the collector. Indeed, the hybrid models that represent both CFD and thermodynamic analyses allow a closer approach to a more realistic system by allowing optimization in both structural and thermal performances. By using the data obtained from solar tracking coupled with CFD analysis, for example, one can simulate how the collector orientation influences the efficiency of heat exchange [24].

2.6.2 Environmental and Climatic Conditions

Environmental factors, especially in the variability of solar radiation and temperature changes, are very important to consider in modeling solar collectors with tracking systems. Several climatic conditions directly influence the amount of captured energy, including periods of cloud cover, changes in ambient temperature, and seasonal changes.

These dynamic climatic conditions have been taken into consideration in more advanced models that incorporate environmental data into tracking and control algorithms.

These models should then incorporate real-time weather data and historical climatic conditions that affect the performance of the tracking system and collector efficiency. Such environmental variables simulated in the models yield more realistic long-term performance predictions of solar collectors for different geographical locations, ensuring that these systems remain efficient under different conditions [25].

Table 4 lists measuring devices and their respective accuracies for monitoring and assessing environmental parameters. The table goes into details on all the sensors for temperature, radiation, and other key variables that will serve as an indication of adjustments in the position of the collector with the view to optimizing performance under dynamic environmental conditions [24].

Table 2. List of measuring devices, sensors and their accuracy

General Value (GV)	Amount	Accuracy
Thermometer Pt100	10	Class B; ± (0.30 K + 0.005 × |t|)
Global radiation sensor FLA613GS	1	cos-error f2 < 3%, linearity < 1%, absolute error < 10%
Almemo 2490-1	1	accuracy ±0.1% of measured value, ±0.1 of final values
Supercal 531	1	Temperature drift ±0.01%/K, Class 2 according to EN 1434-1
Thermometer Pt500	2	Class B; ± (0.30 K + 0.005 × |t|)
Superstatic 440	1	Class 3 according to EN 1434-1

2.7 Modern Methods for Modeling Solar Collectors

Recent advances in solar modeling have increasingly integrated artificial intelligence, with a significant focus on the machine learning optimization of solar energy systems. Of all the AI-based approaches, one of the most promising involves the use of Long Short-Term Memory models, a type of recurrent neural networks (RNN). LSTMs are particularly well-suited to time-series predictions and thus find their ideal application in the modeling of temporal variability both of solar radiation and system performance. These models predict the output of solar power and provide an opportunity to adjust system parameters to optimize real-time performance.

Except for LSTM, various neural networks have been widely applied in general to predict and optimize energy conversion efficiency. AI-driven models, including deep learning networks, have great promise to further improve the performance of the solar tracking system by analyzing big volumes of meteorological and operational data in a dynamic manner, thereby readjusting the positioning of solar panels across the day for optimal energy capture. This ability to learn from history consequently allows AI-based models to make more accurate predictions about future performance for variable climatic conditions [26].

One of the prime issues to be reckoned with in solar energy systems is how the output of the best possible power can be sustained under widely fluctuating environmental conditions, due to continuously changing sunlight intensity and ambient temperature. Because of this challenge, some adaptive maximum power point tracking (MPPT) models have been developed. These work in concert to continuously correct, in real time, operational parameters of solar collectors so that they can operate at maximum efficiency given whatever the prevailing external conditions.

Especially, the MPPT algorithms with AI methods will be more important in power output optimization. With the availability of real-time data on irradiance and temperature, adaptive models thus track the maximum power point of the solar panel with higher precision. Conventional MPPT methods have delays in responding to rapid changes of sunlight, which essentially results in suboptimal generation of power. However, it has been observed that adaptive models using techniques from machine learning, such as LSTM and deep neural networks, can predict these variations and allow more efficient tuning of system parameters accordingly [27], also Deep learning model proof efficiency that in more fields such geographically [28]. This contributes to better overall system performance, higher energy yields.

2.8 Case Studies on Solar Collector Modeling

Various case studies show that modern modeling methods improve the performance of solar collectors. One of the studies is based on a new design in the solar collector for water heating using nanofluids as the working medium. The CFD modeling used AI-driven optimizations in the model, which came up with critical developments in both heat transfer efficiency and overall system performance [26].

Another innovative work proposed a hybrid CFD model of solar thermal collectors, which joined numerical modeling and experimental cross-validation. The hybrid approach that the researchers have chosen thus allowed them to get an optimized thermal performance of the collector for different operating conditions, thus providing helpful information regarding the efficiency of the system in real situations [27].

In such models where environmental conditions are prevailing, dynamic prediction of the behavior of solar collectors has proved very effective; hence, improving energy conversion.

A third one, on nanofluid-based parabolic trough solar collectors, used thermal analysis based on parameter variation. Integrating the AI-based models within CFD simulations allowed the researchers to further optimize the design of the collectors and an improved thermal efficiency with minimum losses in energy was obtained [27].

These case studies bring into view the large possibilities of modern modeling methods, especially when combined with AI in enhancing efficiency and reliability in solar energy systems. Advanced modeling techniques will continue to play an important role in optimizing solar collector performance for varying climatic conditions as solar technology evolves.

3.0 KEY INSIGHT

The presented overview of the modern methods of solar collector modeling has shown huge steps forward in both theoretical and empirical approaches in this area. In particular, the integration of artificial intelligence and machine learning, mainly through models like LSTM networks, has brought a new dimension for enhancing solar tracking systems. These AI-driven methodologies can capture a level of complexity given by a real-time environment that sometimes traditional models have not been able to adapt to easily. It has been found from several works that LSTM models work wonders when applied for time-series forecasting and are considered great for prediction of the energy output and optimization of the tracking mechanisms in solar collectors. The neural networks, together with sophisticated algorithms for MPPT, could run continuous adjustments that would enable the achievement of peak efficiency even at fluctuating conditions of solar radiation [3].

Meanwhile, the introduction of CFD and hybrid modeling has clearly shown significant structural and thermal improvements for solar collectors. CFD, coupled with empirical validation, has therefore enabled precision in the regulation of fluid dynamics flow, coupled with heat exchange within the system. This is particularly relevant for PTCs, for which the interaction of the heat transfer medium with the solar receiver is relevant in terms of system efficiency. The thermodynamic model, in the process of hybridization with CFD, would give a wider perspective on how solar collectors could adapt to both mechanical and environmental stressors [20].

The review has also focused on the role of nanofluid-based collectors, which improve thermal efficiency. Indeed, several studies have demonstrated that the incorporation of nanotechnology within collectors can lead to a substantial improvement in energy conversion efficiency. AI models have been effective in fine-tuning these systems and thus enabling optimized performance in varied climatic conditions. Among the main findings from the literature review is that AI and hybrid models can reduce energy losses and maximize system efficiency at variable conditions [2].Summarization on the reviewed work is as listed in Table 5.

Table 3. Summary of Reviewed Studies

Study	Key Focus	Modeling Approach	Conclusions	Limitations
Kumar et al. (2023) [26]	Solar collectors with nanofluids for water heating	CFD modeling and AI-driven optimizations	Significant improvements in heat transfer efficiency and overall system performance through AI-driven modeling.	High computational cost and need for extensive validation.
Nokhosteen & Sobhansarbandi (2021) [27]	Hybrid CFD model for solar thermal collectors	Numerical modeling combined with experimental validation	Optimized thermal performance and efficiency across various operating conditions.	Increased complexity and computational resource requirements.
Bellos et al. (2020) [2]	Nanofluid-based parabolic trough solar collectors	Parametric thermal analysis with AI integration	Improved thermal efficiency and reduced energy losses by employing AI-based models in CFD simulations.	Dependency on large datasets for training AI models.

Study	Key Focus	Modeling Approach	Conclusions	Limitations
Ahmadi et al. (2023) [1]	Thermal and optical enhancement of low-temperature collectors	Analytical and empirical models	Enhanced optical and thermal efficiency of solar collectors under varying climatic conditions.	Limited accuracy in complex, dynamic conditions.
Verma et al. (2020) [3]	Design and process analysis for solar thermal conversion	Thermodynamic and empirical models	Improved energy conversion rates through optimized design and working fluid selection.	Simplifications reduce precision in real-world applications.

4.0 CONCLUSION

This review has critically analyzed some of the main contemporary methods applied in the modeling of solar collectors, with a specific focus on integration with solar tracking systems and state-of-the-art modeling approaches like AI and hybrid methods. The literature review identifies key milestones that have been achieved so far toward the optimization of the performance of solar collectors using different climatic conditions. The integration of AI, especially Long Short-Term Memory or LSTM models with neural networks, has really shown tremendous promise for improving Solar Tracking Systems by making real-time adjustments and enhancing prediction capability to improve energy conversion efficiency.

Besides, many more developments have been made in CFD and hybrid models while showing enhancements in the complex physical and thermal behaviors of solar collectors, then ensuing in improved structural stability and thermal management. The inclusion of nanofluids as working mediums has increased further thermal efficiency in solar systems and introduced a new frontier in solar energy research. These developments have led to increased energy output, as well as more reliable solar systems that can be adapted to suit a wider range of environmental conditions.

The review has indicated that modern modeling techniques are very important for further development in solar energy, given the rapid growth of energy demand and further energy sustainability. In fact, the application of AI, hybrid models, and innovative materials such as nanofluids will lie at the heart of enhancing performance and efficiency in solar collectors as technology evolves in the realm of solar systems.

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