

Review

Adaptive and Stepwise Solar Tracking Systems in Flat-Plate and Tubular Collectors: A Comprehensive Review of Thermal Performance, Modeling, and Techno-Economic Perspectives

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Abstract

Solar thermal collectors remain a fundamental component of renewable heat generation in the building sector. Recent progress in solar tracking technologies has led to the emergence of adaptive and stepwise tracking systems that enhance radiation capture while maintaining low mechanical and energy demands. This review comprehensively synthesizes current knowledge on the design, modeling, and performance evaluation of such systems, with emphasis on their role in building decarbonization and techno-economic feasibility. The classification of collectors is revisited to highlight the relationship between optical concentration, tracking precision, and thermal output. Comparative studies indicate that adaptive and stepwise tracking strategies improve annual energy yield by 20–35% compared to fixed systems, while reducing the levelized cost of heat (LCOH) by up to 15%. Modeling approaches integrating optical and thermal domains are discussed alongside emerging applications of artificial intelligence, predictive control, and IoT-based monitoring. The paper concludes with an outlook on future research directions, focusing on durability, standardization, and digital integration of solar thermal systems in smart buildings. Overall, adaptive tracking technologies represent a promising pathway toward efficient and sustainable solar heat utilization in the context of global energy transition.



Academic Editor: S. A. Sherif

Received: 17 October 2025

Revised: 17 November 2025

Accepted: 19 November 2025

Published: 21 November 2025

Citation: Kowalik, R. Adaptive and Stepwise Solar Tracking Systems in Flat-Plate and Tubular Collectors: A Comprehensive Review of Thermal Performance, Modeling, and Techno-Economic Perspectives. *Energies* **2025**, *18*, 6106. <https://doi.org/10.3390/en18236106>

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Keywords: adaptive solar tracking; stepwise tracking; solar thermal collectors; flat-plate collectors; evacuated-tube collectors; building decarbonization; thermal modeling; renewable heat systems

1. Introduction

The decarbonization of the global building sector has become one of the central challenges in achieving sustainable development and climate neutrality. Buildings account for roughly 30–40% of total final energy consumption and about one-third of global CO₂ emissions, with the majority of this demand linked to space heating and domestic hot water production [1]. Achieving international climate goals, including those set by the Paris Agreement and the European Green Deal, requires a profound transformation of the way heat is produced and consumed in buildings [2].

Among available renewable technologies, solar thermal systems are recognized as a particularly efficient and mature option for producing low- and medium-temperature heat. Unlike photovoltaic (PV) systems that convert sunlight into electricity, solar thermal collectors convert solar radiation directly into heat, offering high conversion efficiency, long lifetime, and relatively low maintenance costs [3]. They can be effectively applied in

domestic hot water systems, space heating, industrial preheating, or solar-assisted heat pumps [4]. The International Energy Agency estimates that solar thermal technologies could supply up to 20–25% of global low-temperature heat demand by 2050, offsetting nearly 800 million tonnes of CO₂ emissions annually [5].

In Europe, the role of solar thermal technologies is further emphasized by the Renewable Energy Directive (RED III), which identifies renewable heat as a key pillar of the energy transition [6]. The European Solar Thermal Technology Platform (ESTTP) foresees that solar heat could cover about 25% of the total heating demand in buildings by 2050, particularly in combination with district heating, seasonal storage, and hybrid systems [7]. Despite this potential, the deployment of solar thermal collectors is often constrained by their fixed installation geometry. Most collectors are optimized for a specific tilt and azimuth angle, which maximizes annual radiation only during part of the year. In regions with continental or temperate climates, where the solar altitude varies by more than 45° between winter and summer, the mismatch between solar availability and heating demand becomes particularly significant [8].

As a result, the annual thermal efficiency of fixed flat-plate collectors (FPCs) rarely exceeds 45–55%, and much of the available radiation remains unused [9]. To address this issue, various solar tracking mechanisms have been developed to continuously or periodically adjust the collector's orientation to follow the Sun. By maintaining a near-normal incidence angle between the collector surface and solar rays, tracking systems can increase the amount of absorbed radiation by 30–45% compared to fixed configurations [10]. However, fully continuous tracking introduces higher investment and operational costs, mechanical complexity, and energy consumption for actuator control, which limit its application in small- and medium-scale building systems [11].

For this reason, recent research has focused on simplified tracking concepts such as stepwise (discrete) and adaptive tracking. Stepwise systems perform rotation in predefined angular steps (e.g., 10°, 15°, or 30°) rather than continuously, while adaptive systems modify the step size dynamically based on solar irradiance or meteorological conditions [12]. These approaches can recover most of the energy benefits of continuous tracking while significantly reducing wear, energy consumption, and control complexity. Studies have shown that for rotation steps between 10° and 15°, the collected radiation may reach 90–95% of that obtained with continuous tracking [13].

Such simplified tracking methods are especially suitable for low-energy and nearly zero-energy buildings (nZEBs), where compactness, durability, and low maintenance are essential. In addition, the growing integration of digital control, predictive algorithms, and Internet of Things (IoT) devices enables intelligent management of solar thermal systems [14]. Adaptive and hybrid tracking mechanisms, when combined with advanced control logic, allow for further optimization of energy use under variable weather conditions, including partly cloudy or diffuse-dominated days [15].

The environmental and economic advantages of solar thermal collectors also extend beyond operational performance. Life cycle assessments (LCA) indicate that the energy payback time (EPBT) of modern flat-plate and evacuated tube collectors typically ranges between 1.5 and 3 years, while the carbon payback time is often below two years [16]. This makes solar thermal technologies one of the fastest-returning renewable energy investments in the heating sector. Their integration into hybrid systems—combining solar collectors with heat pumps, thermal storage, or photovoltaic–thermal (PVT) modules—further enhances system flexibility and reduces dependency on conventional energy sources [17].

Given these advantages, solar thermal technologies, particularly those employing innovative tracking mechanisms, are expected to play a central role in the decarbonization of the building sector. Their adaptability to various climatic conditions, potential for inte-

gration into intelligent control systems, and high environmental performance make them a cornerstone of future low-carbon, resilient, and energy-efficient building infrastructure [18].

The next section provides a concise classification of solar thermal collectors and tracking configurations, highlighting the operating principles, structural design, and performance differences between flat-plate, glass tube, and concentrating systems.

2. Classification of Solar Collectors and Tracking Systems

Solar thermal collectors are devices designed to capture incident solar radiation and convert it into useful thermal energy. Their development has evolved over several decades, leading to a wide range of configurations adapted to different climatic, economic, and technological contexts [19]. Generally, solar collectors are categorized according to (i) the concentration ratio and (ii) the tracking mechanism employed to follow the Sun's apparent movement.

Solar thermal technologies can be broadly categorized according to collector geometry, heat-transfer mechanism, and tracking configuration. The tracking concept defines the ability of the collector to maintain optimal orientation toward the Sun and thus strongly influences optical and thermal efficiency [19–21] (Figure 1).

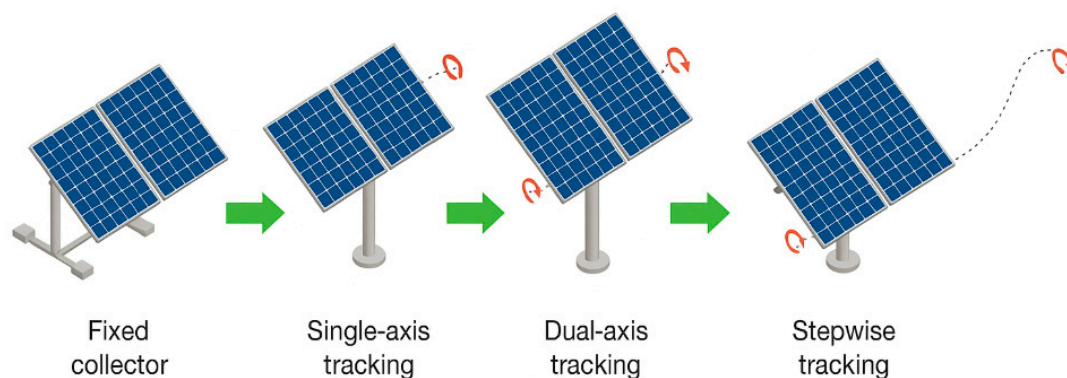


Figure 1. Evolution of solar thermal collector and tracking configurations: from fixed installations to adaptive and intelligent tracking systems.

2.1. Types of Solar Thermal Collectors

From the optical and structural point of view, solar thermal collectors can be divided into non-concentrating and concentrating systems [20].

Non-concentrating collectors—which include flat-plate collectors (FPCs) and evacuated or glass-tube collectors (ETCs/GTCs)—have the absorbing surface exposed to both direct and diffuse solar radiation. They operate at relatively low temperatures (typically below 120 °C) and are the most common choice for residential and small-scale applications [21].

Flat-plate collectors are characterized by a simple structure: an absorber plate coated with a selective layer, transparent glazing to reduce convective losses, and insulation at the rear and sides [22]. They are cost-effective, reliable, and easy to integrate into building envelopes, which explains their wide use in domestic hot water systems and solar space heating [23].

Evacuated or glass-tube collectors, on the other hand, use cylindrical absorbers enclosed in vacuum-sealed glass tubes to minimize thermal losses. This configuration provides better performance in cold or windy climates, as well as under diffuse or partly cloudy conditions [24]. Their efficiency advantage over FPCs becomes particularly significant when the temperature difference between the collector and the ambient air exceeds 40 °C [25].

Concentrating collectors, such as parabolic trough collectors (PTCs), linear Fresnel reflectors, and compound parabolic concentrators (CPCs), use reflective or refractive surfaces to focus solar radiation onto a smaller absorber area. They are capable of reaching higher operating temperatures (up to 400 °C or more) but require precise solar tracking and are generally employed in industrial or large-scale solar thermal power plants [26].

The distinction between non-concentrating and concentrating collectors thus determines not only their optical design but also the necessity and complexity of the tracking mechanism.

2.2. Classification of Solar Tracking Mechanisms

Solar tracking mechanisms aim to maximize the amount of solar radiation incident on the collector surface by adjusting its position in real time or at defined intervals. Depending on their degrees of freedom, axis orientation, and control strategy, several types of tracking systems can be identified [27].

(a) Degrees of freedom

- ✓ Single-axis tracking (SAT): The collector rotates around one fixed axis, usually aligned along the north–south direction, allowing the surface to follow the daily east–west movement of the Sun. SAT configurations can improve annual energy gains by about 30–35% compared to fixed installations [28].
- ✓ Dual-axis tracking (DAT): The collector can rotate about two perpendicular axes, enabling continuous alignment with the Sun in both azimuth and elevation. DAT systems offer the highest energy yield—often 40–45% above stationary setups—but also involve higher costs, greater mechanical wear, and higher energy use for actuation [29].

(b) Orientation of the rotation axis

Depending on the installation site and design constraints, the rotation axis may be horizontal, vertical, tilted, or polar-aligned [30].

- ✓ Horizontal east–west axes are most common for single-axis tracking in building applications.
- ✓ Tilted north–south axes are more suitable for higher latitudes, as they maintain a better angular relationship with the solar trajectory throughout the year.
- ✓ Vertical or polar-oriented axes are typically used in compact or experimental systems, where mechanical constraints limit the range of motion [31].

Each configuration offers a trade-off between tracking accuracy, shadowing risk, and structural simplicity. The north–south aligned SAT is often preferred in moderate continental climates, where the diurnal solar path shows strong variation between summer and winter [32].

(c) Control approach

Solar tracking can also be categorized by the control strategy used to determine the collector's movement:

- ✓ Open-loop systems rely on preprogrammed astronomical equations or solar position algorithms. They are simple, robust, and suitable for predictable conditions.
- ✓ Closed-loop systems use feedback from light sensors, pyranometers, or temperature differences to continuously correct the collector's position. These are more precise but also more sensitive to component failure.
- ✓ Hybrid systems combine both approaches, typically operating in open-loop mode while applying closed-loop corrections when irradiance fluctuates due to cloud cover or transient shading [33].

2.3. Stepwise and Adaptive Tracking

In recent years, attention has shifted toward stepwise and adaptive tracking approaches that balance energy efficiency with mechanical simplicity [34].

Stepwise tracking (also referred to as discrete tracking or relative single-axis tracking) involves adjusting the collector's position at predefined angular steps rather than continuously. The collector remains stationary for a certain period and then performs a short, rapid movement to a new orientation. Depending on the chosen rotation step ($\psi = 1\text{--}90^\circ$), the number of movements per day can vary from a few to several dozen [35]. Experimental and numerical studies have demonstrated that stepwise tracking with $\psi = 10\text{--}15^\circ$ can achieve 90–95% of the total daily energy yield of continuous tracking, while reducing mechanical wear and energy use by up to 80% [36].

Adaptive tracking represents a more advanced approach, where the rotation step or activation frequency is dynamically modified according to real-time solar irradiance, beam-to-diffuse ratio, or predictive weather data. This strategy allows the collector to reduce unnecessary movements during cloudy conditions, improving both reliability and cost-effectiveness. Adaptive algorithms are increasingly supported by microcontrollers, IoT-based monitoring, and machine learning models, which enable predictive optimization of tracking schedules [37].

These simplified or intelligent tracking methods are particularly suitable for flat-plate and glass-tube collectors integrated into building-scale systems. They ensure high energy efficiency with minimal operational complexity—an important feature for low-energy and nearly zero-energy buildings (nZEBs) [23].

2.4. Summary of Classification Criteria

As illustrated in Figure 2, stationary collectors include flat-plate and evacuated-tube types, while moving systems employ single- or dual-axis tracking mechanisms combined with concentrating geometries such as parabolic troughs, Fresnel lenses, or heliostat fields. This classification provides a clear structural basis for analyzing the thermal and optical performance summarized in Table 1.

first criterion of division		second criterion of division		
tracking	fixed	flat collectors		non -focusing
		vacuum collectors		
		complex parabolic collectors		
	single-axis tracking SAT	parabolic trough collectors		Linear
		linear Fresnel lens collectors		
		cylindrical trough reflectors		
	dual-axis tracking DAT	parabolic lens collectors		Point-focus
		heliostat fields		
		circular Fresnel lens		
			focusing	

Figure 2. Classification of solar thermal collectors according to motion (I criterion) and concentration geometry (II criterion).

Table 1. Summary of the main categories of solar thermal collectors and tracking configurations, indicating their relative energy gains, mechanical complexity, and typical areas of application [26].

System Type	Axis Configuration	Energy Gain vs. Fixed	Complexity	Typical Use
Fixed Collector	—	—	Very low	Domestic water heating, small-scale buildings
Single-Axis Tracking (SAT)	N–S horizontal or tilted	+30–35% [28]	Moderate	Residential buildings, nZEBs
Dual-Axis Tracking (DAT)	Azimuth + elevation	+40–45% [29]	High	Large-scale solar fields
Stepwise Tracking (rSAT)	Discrete rotation ($\psi = 10\text{--}15^\circ$)	+25–30% [36]	Low–moderate	Hybrid systems, residential applications
Adaptive Tracking	Variable ψ , sensor/predictive control	+30–40% [37]	Moderate	Smart buildings, research systems

Solar tracking thus represents a key design variable in optimizing the thermal performance of solar collectors. The choice between fixed, stepwise, or adaptive operation depends on the intended application, local climate, and economic considerations. The next section focuses on the thermal and optical behavior of stepwise and adaptive tracking collectors, emphasizing recent advances in their experimental and numerical characterization.

Recent advances in materials science, control electronics, and data analytics have significantly influenced the development of solar tracking systems. Lightweight composite structures, high-torque stepper motors, and low-cost microcontrollers have made stepwise and adaptive tracking more feasible for small and medium-sized installations [38]. Moreover, modern control architectures often incorporate predictive algorithms based on solar position models or short-term irradiance forecasts, improving tracking accuracy without the need for complex sensor arrays [38].

Digitalization and the emergence of Internet of Things (IoT) platforms have also facilitated real-time monitoring and fault detection, reducing maintenance requirements and improving long-term reliability [39]. As a result, solar tracking—once limited to large-scale solar fields—is increasingly being integrated into building-integrated solar thermal (BIST) systems, where compact geometry and low visual impact are required [40].

Despite these advancements, several design challenges remain. The integration of tracking mechanisms into building envelopes often raises concerns related to wind loads, structural stability, and esthetic constraints. Mechanical durability and control reliability are also critical, especially in cold or humid climates, where icing or component fatigue can impair performance [41].

Ongoing research therefore focuses on optimizing the trade-off between mechanical simplicity, energy gain, and economic viability. Hybrid tracking systems—combining limited angular motion with adaptive control—appear particularly promising, providing substantial performance improvements without excessive structural complexity [42].

In summary, the classification of solar thermal collectors and tracking systems reflects both the technological diversity and the growing trend toward simplification and adaptability. Stepwise and adaptive tracking approaches, in particular, represent a practical compromise between energy performance and system reliability. The next section reviews recent studies that have analyzed the thermal and optical performance of stepwise tracking flat-plate collectors, highlighting their development from early conceptual models to contemporary experimental and numerical research.

In recent years, the research focus on solar tracking systems has shifted from conventional mechanical designs toward intelligent and adaptive control strategies. The rapid progress in sensor technology, low-cost microcontrollers, and artificial intelligence has significantly stimulated scientific output in this domain. To visualize this evolution, Figure 3

illustrates the research trends from 2010 to 2025 based on a keyword analysis of publications indexed in the Scopus database. The results reveal a steady increase in the total number of studies on solar tracking, with particularly strong growth in adaptive and stepwise tracking topics after 2020. This trend reflects the global transition from basic actuation mechanisms to advanced optimization and predictive control approaches for both flat-plate and tubular collector systems.

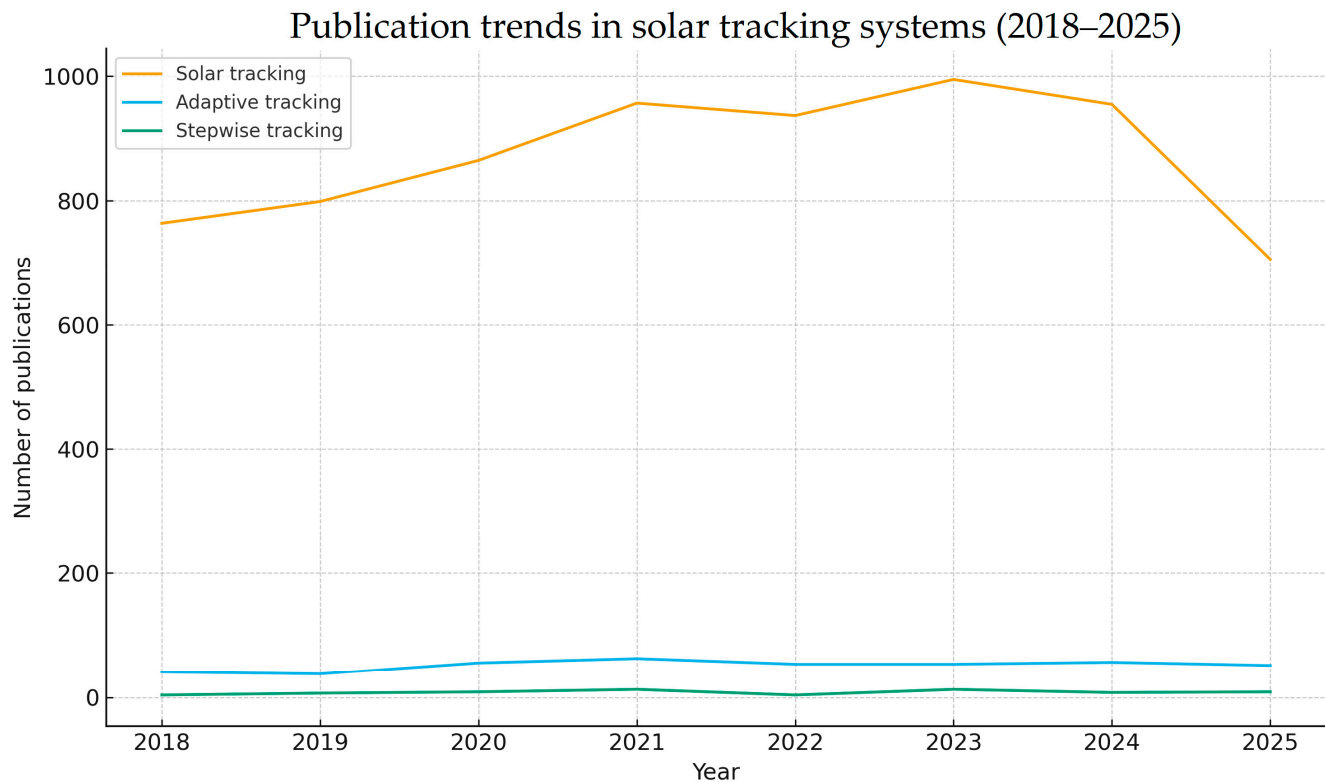


Figure 3. Publication trends in solar tracking systems (2018–2025) based on a Scopus keyword analysis. Data source: Scopus (Elsevier), search performed in January 2025 using the keywords “solar tracking”, “solar adaptive tracking” and “solar stepwise tracking”. Only journal articles and reviews were included.

The bibliometric dataset was obtained from the Scopus database (Elsevier), covering the years 2010–2025. The search included the keywords “solar tracking”, “stepwise tracking”, “adaptive tracking”, and related terms, filtered to journal articles and reviews in English.

To complement the quantitative publication trends presented in Figure 3, a keyword co-occurrence analysis was performed to identify the conceptual structure of research related to solar tracing and solar tracking. The resulting network, shown in Figure 4, reveals three dominant thematic clusters. The first and largest cluster is associated with optical modeling, including terms such as “ray tracing”, “solar concentrators”, “reflection”, and “optical efficiency”, indicating the strong role of geometric and Monte-Carlo simulation in tracking-related studies. The second cluster aggregates keywords related to solar radiation and solar energy applications, highlighting the link between tracking performance and irradiance modeling. The third cluster focuses on photovoltaic and thermal system performance, where terms such as “heat transfer”, “efficiency”, and “photovoltaic cells” reflect operational and energy-conversion aspects. Together, these clusters confirm that research on solar tracking is distributed across optical design, irradiance modeling, and system-level performance analysis.

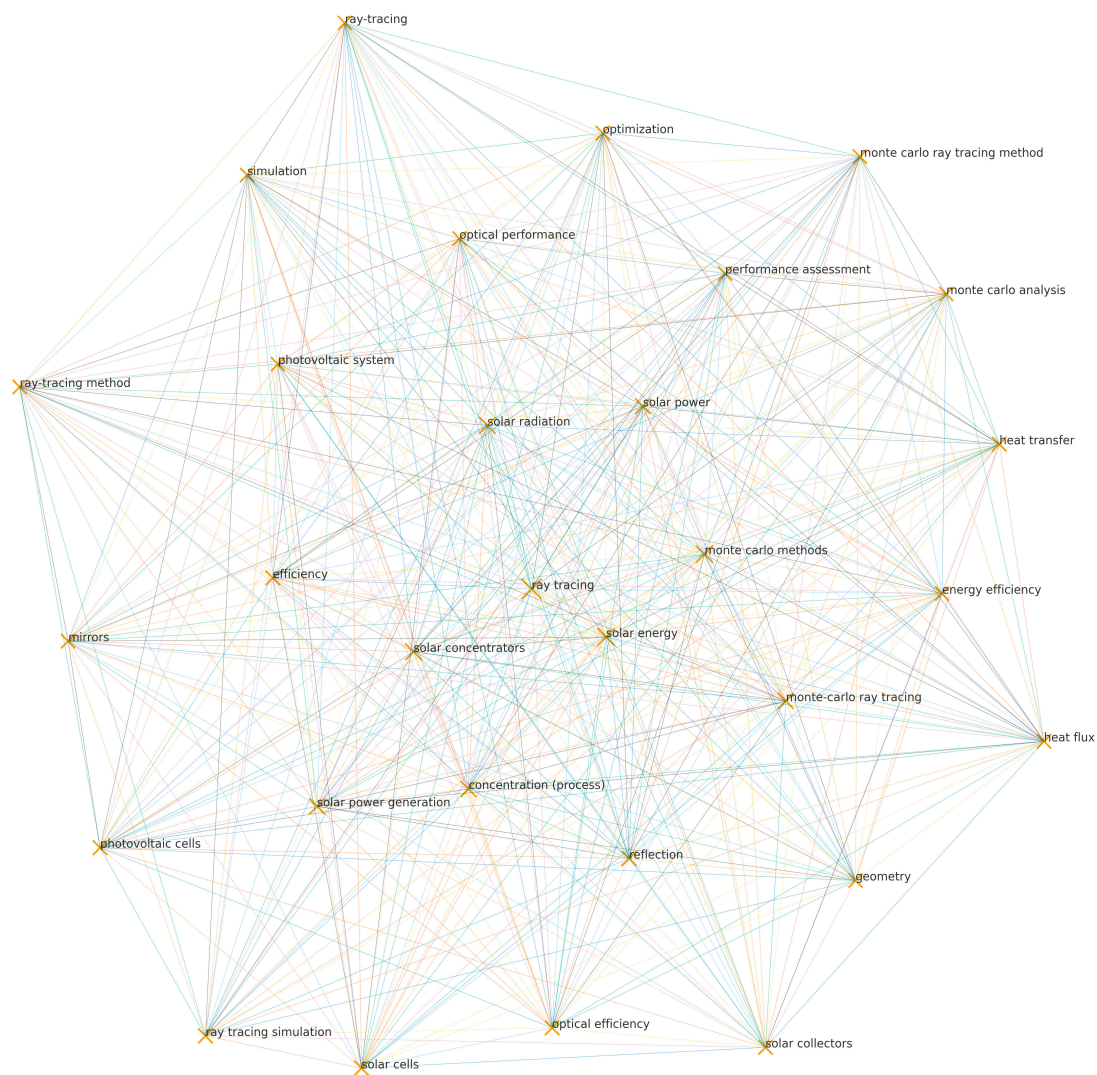


Figure 4. Keyword co-occurrence network for research on solar tracing and solar tracking (Scopus, 2010–2025). Only the 30 most frequent keywords are shown. Node size is proportional to frequency of occurrence; edges indicate co-occurrence in the same publication. Data source: Scopus (Elsevier), export performed in November 2025.

The above classification of solar collector and tracking configurations forms the conceptual basis for positioning past and current research within a consistent analytical framework. To illustrate the technological evolution and the range of methodological approaches investigated over the last three decades, Table 2 provides a consolidated overview of representative studies on tracking systems—covering flat-plate, tubular, and heliostat collectors—together with their evaluation methods and reported performance gains.

Table 2 provides a consolidated overview of representative studies covering classical single- and dual-axis tracking, the development of stepwise and adaptive tracking systems, and key advances in heliostat tracking control. The table integrates both historical contributions and recent experimental and modeling work (2010–2025), highlighting the progression toward simplified, low-energy and intelligent tracking strategies relevant for flat-plate and tubular collectors.

Table 2. Summary of key studies on solar tracking systems in flat-plate, tubular, and heliostat collectors (1995–2025).

Authors	Year	Tracking Type	Methodology	Evaluation Approach	Compared with	Main Findings/Energy Gain	References
Khalifa	1998	aSAT/rSAT	Geometric simulation	Clear-sky irradiance	Fixed collector	90–95% of continuous tracking energy with 10–15° steps	[43]
Mehleri et al.	2010	Single-axis/discrete	Numerical simulation (Greece, Central Europe)	Seasonal irradiance	Fixed	~30% energy gain with optimized axis orientation	[44]
Mumba	1995	Manual tracking	Experimental	Daily performance	Fixed	Up to 80% increase in thermal efficiency; performance highly sensitive to tracking frequency and operator accuracy; results remain a benchmark for manual tracking effectiveness.	[45]
Shaltout et al.	1995	SAS Version 6.09 statistical software (SAS Institute Inc., Cary, NC, USA)	Experimental	Field tests	V-trough	~23% energy increase; V-trough geometry improved beam concentration while maintaining low mechanical complexity, demonstrating feasibility of passive-enhanced tracking.	[46]
Ibrahim	1996	SAS Version 6.11 statistical software (SAS Institute Inc., Cary, NC, USA)	Experimental	Field tests	Two-stage concentrator	62–77% gain depending on optical concentration ratio and cooling strategy; confirmed suitability of tracking with two-stage concentrators in high DNI climates.	[47]
Khalifa & Abbas	2009	Discrete tracking	Simulation	Daily clear-sky	Continuous tracking	Optimal 15° increment retains ~92% energy	[48]
Al-Othman et al.	2023	Hybrid SAT	Experimental	Daytime multi-season	Fixed	27% gain; reduction in actuator motion	[49]
Santos de Araújo et al.	2024	Adaptive discrete	Numerical	Seasonal analysis (Brazil)	Fixed	+28–32%; adaptive steps reduce movements by 70%	[50]
Kumba et al.	2024	Stepwise	Experimental (Energy Reports)	Real-sky	Fixed	+25–30%; field validation of discrete strategies	[51]
Flores-Hernández et al.	2021	Dual-axis tracking (optimized strategy)	Analytical optimization + numerical simulation + experimental validation	Outdoor performance assessment under clear and cloudy sky with real-sky irradiance fluctuations	Fixed PV/thermal configuration	+20–30% improvement in useful energy; performance sensitivity strongly related to diffuse fraction; stepwise actuation reduces tracking movement relative to continuous control	[52]
Azam et al.	2024	Semi-continuous tracking	Experimental + numerical modeling	Outdoor tests under clear and partially cloudy sky	Fixed-tilt PV system	Semi-continuous tracking algorithm increases energy yield by approx. 20–30% compared to a fixed system, while reducing the number of actuator operations by about one third, thus lowering mechanical wear and control effort	[53]

Table 2. Cont.

Authors	Year	Tracking Type	Methodology	Evaluation Approach	Compared with	Main Findings/Energy Gain	References
Batayneh et al.	2019	Single-axis discrete (stepwise)	Experimental + numerical	Clear sky and days with partial cloud cover (summer, Irbid)	Continuous single-axis tracker	Discrete tracker with only three azimuthal movements per day collected $\approx 91\text{--}94\%$ of the energy of a continuous single-axis tracker, with a very large reduction in the number of actuator operations +22% gain; hybrid time-sensor control increased stability under mixed sky and reduced actuator oscillations during rapid irradiance transitions.	[54]
Manna et al.	2023	Hybrid (time + sensor)	Numerical + experimental	Seasonal	Fixed		[55]
Pargmann et al.	2020	Heliostat adaptive	Experimental (DLR/PSA)	Closed-loop aiming error	Continuous	Improved tracking precision ($<0.5^\circ$ pointing error); significant reduction in heliostat aiming drift, enabling higher receiver flux uniformity in CSP towers.	[56]
Fuentes-Morales et al.	2021	Solar tower control	Hybrid predictive control	Simulation + calibration	Continuous	Hybrid predictive tower control lowered cumulative tracking error 30–40% vs. classical open-loop aiming; improved flux stability and reduced thermal runaway risk.	[57]
González-Camarillo et al.	2022	ML-based heliostat tracking	ANN optimization	Experimental	Continuous	Predictive algorithm reduces tracking error by 35%	[58]
Carballo et al.	2023	RL-based heliostat coordination	Simulation	Field layout	Continuous	RL control improved heliostat coordination and power delivery to receiver by 4–7%; particularly beneficial in complex field geometries with partial shading.	[59]
Ya’u	2017	Classification of tracking systems	Literature review	Comparison of tracking system types (single-/dual-axis; passive vs. active)	—	Established a widely adopted classification framework; summarized benefits and drawbacks of geometric, sensor- and hybrid-controlled tracking systems	[60]
Sadeghi et al.	2025	Overview of modern STS (SAT/DAT, adaptive, AI/ML-RL control)	Systematic literature review + comparative performance assessment	Climatic and operational scenarios (modeling and field data synthesis)	Fixed and continuous tracking (literature benchmark)	Identifies next-generation trends: hybrid predictive control, AI-based optimization, actuator wear reduction; reported energy gains of 20–40% depending on climate and control strategy	[15]
Huang et al.	2023	Single-axis optimized tracking	Experimental + algorithm development (orientation optimization)	Outdoor evaluation under clear and partially cloudy sky	Fixed PV array	Improved power output by $\approx 17\text{--}26\%$; tracking algorithm reduces unnecessary actuator movement, enhancing long-term system stability	[61]

Table 2. Cont.

Authors	Year	Tracking Type	Methodology	Evaluation Approach	Compared with	Main Findings/Energy Gain	References
Sattler et al.	2020	Heliostat tracking and calibration strategies	Review of calibration and closed-loop aiming methods	Comparative assessment (kinematic, optical and vision-based calibration)	Continuous aiming systems (tower CSP)	Demonstrated that improved calibration techniques reduce pointing error to $<0.5^\circ$, increasing effective heliostat optical efficiency and delivered thermal flux	[62]
Sievers et al.	2025	Hybrid heliostat tracking (neural-network-assisted calibration)	End-to-end sensitivity analysis using physics-informed neural networks	Simulation + performance sensitivity metrics (aiming error, optical flux distribution)	Standard heliostat calibration/control approach	Hybrid NN calibration method reduced aiming error and improved target flux uniformity; analysis identifies key sensitivities for next-generation heliostat tracking systems	[63]

3. State of the Art in Stepwise Tracking of Flat-Plate Collectors

The concept of stepwise, or discrete, solar tracking for flat-plate collectors (FPCs) emerged as a response to the mechanical and economic limitations of continuous tracking systems. The idea was to retain most of the energy benefits of continuous solar alignment while minimizing the number of mechanical movements and energy consumption for actuation [64]. Over the last two decades, this concept has evolved from simplified geometric analyses to advanced numerical simulations and, more recently, experimental validation under real operating conditions [57].

3.1. Early Conceptual and Geometric Models

The first studies on discrete tracking systems appeared in the early 2000s by Khalifa [43]. In the absolute single-axis tracking (aSAT) approach, the collector changes its position by a constant angular increment with respect to a fixed frame (e.g., $\psi = 15^\circ$ every hour). In contrast, the relative single-axis tracking (rSAT) strategy defines the collector's movement with respect to the instantaneous direction of incoming solar radiation, which ensures improved angular conformity between the aperture plane and the radiation vector, although it may lead to non-uniform step durations [32].

Khalifa's simulations demonstrated that stepwise tracking with angular increments of $10\text{--}15^\circ$ could achieve more than 90% of the radiation gain obtained from continuous tracking. These findings were later confirmed by Mehleri et al. (2010), who analyzed the influence of step size and axis orientation on total incident irradiance in Central European climates [44]. Both studies highlighted that tracking efficiency strongly depends on the solar altitude profile and daily beam-to-diffuse radiation ratio.

Subsequent works focused on optimizing the rotation schedule, aiming to reduce unnecessary movements during periods of low solar elevation. Santos de Araújo et al. (2024) and Kumba et al. (2024) demonstrated that adaptive stepwise tracking can significantly improve the energy-to-motion ratio, achieving comparable gains to continuous systems with up to 70–80% fewer actuator operations [50,51].

3.2. Numerical and Seasonal Simulation Studies

With the growing availability of numerical tools such as TRNSYS (Thermal Energy System Specialists, <https://www.trnsys.com>), EnergyPlus (U.S. Department of Energy, <https://energyplus.net>), and MATLAB-based control simulators (MathWorks Inc., Natick, MA, USA, <https://www.mathworks.com>), stepwise tracking began to be analyzed in a seasonal and climatic context. These studies allowed researchers to capture the effect of temperature, diffuse radiation, and ambient conditions on thermal efficiency [65].

Recent contributions by Kowalik and Nešović (2023–2025) expanded the scope of analysis by coupling optical and thermal models of stepwise tracking flat-plate collectors under continental climate conditions [66,67]. Their simulations showed that for rotation steps between 10° and 15° , the daily energy gain ranged from 26% to 33% compared to a fixed collector, depending on season and weather conditions. The results also indicated that in regions with moderate solar altitude (such as Central Poland or Northern Serbia), a step size of 10° provides the optimal balance between radiation capture and actuator stability.

In an extended study, Nešović (2024) [66] incorporated the effect of inlet temperature and collector construction (T1–T3 types) on seasonal efficiency. By modeling five representative summer days, the author demonstrated that adaptive stepwise tracking can enhance annual thermal efficiency by up to 12% relative to a fixed configuration, while maintaining mechanical simplicity [68]. These results support the growing consensus that stepwise systems can achieve near-optimal solar alignment without the need for complex dual-axis mechanisms.

Several other numerical investigations have explored hybrid or sensor-assisted tracking. Manna et al. (2023) proposed a semi-adaptive stepwise controller that adjusts the rotation interval according to solar altitude thresholds [55], while Boa et al. (2022) combined discrete motion with a fuzzy control algorithm to optimize the tracking schedule [69]. Both approaches confirmed that even partial automation—when supported by predictive control—can substantially increase system reliability and operational life.

3.3. Experimental Validation and Field Performance

Although numerical studies have established the theoretical advantages of stepwise tracking, experimental validation under real outdoor conditions remains limited. Laboratory-scale prototypes and small field installations have, however, provided valuable insights into the practical performance of these systems.

Kowalik and Nešović (2025) carried out one of the first comparative experiments under cloudy-sky conditions, evaluating the performance of a glass tube collector with relative single-axis tracking (rSAT) and a flat-plate collector without tracking [68]. The study revealed that while tracking improves beam radiation capture, its benefits diminish under predominantly diffuse radiation. Nonetheless, the glass tube collector maintained superior performance due to its cylindrical geometry and reduced convective losses.

Other experimental investigations, such as those by Flores-Hernández et al. (2024), confirmed that stepwise tracking significantly reduces mechanical wear and energy demand for actuation, without compromising long-term energy yield [52]. Field results typically show energy gains of 20–35% compared to fixed collectors, depending on climatic conditions and step size.

Additionally, tests conducted in moderate climates (Germany, Poland, Czech Republic) indicated that tracking is most beneficial during shoulder seasons (spring and autumn), when the solar altitude is moderate and diffuse radiation fractions are low. These results highlight the need for seasonal optimization of stepwise systems, where the rotation step could vary with solar declination and local cloud patterns.

Although most previous works relied on numerical modeling and simulation tools, several studies have verified the effectiveness of stepwise and adaptive tracking through outdoor experiments. Omeiza et al. (2024) reported that a stepwise-tracked flat-plate collector achieved up to 28% higher daily thermal output than a fixed configuration under variable sky conditions [70]. Manna et al. (2023) demonstrated that a hybrid (time + sensor-based) control mode improved useful heat gain in evacuated-tube collectors by 22% [55]. Similarly, Maoulida et al. (2025) validated model predictions using field data, showing less than 5% deviation between measured and simulated efficiency curves [71]. These

findings confirm that stepwise tracking can deliver tangible thermal and energy gains under real-world operating conditions, not only in theoretical simulations.

3.4. Comparative Performance and Design Optimization

Comparative studies between continuous, stepwise, and adaptive tracking strategies have shown that the marginal energy benefits of continuous tracking often do not justify its mechanical complexity [72]. Stepwise and adaptive systems offer an attractive middle ground, achieving high energy yield with significantly lower investment and maintenance costs.

Recent work by Kabeyi and Olanrewaju (2023) further introduced cost-related metrics such as the Levelized Cost of Heat (LCOH) and Tracking Efficiency Index (TEI), which combine energy output, actuator energy consumption, and system cost in a single framework [73]. Their analysis confirmed that stepwise tracking with $\psi = 10\text{--}15^\circ$ and optimized north–south axis orientation yields the best techno-economic performance for continental climates.

Optimization techniques such as multi-criteria decision-making (MCDM), genetic algorithms, and response surface methods have also been applied to refine step size selection, axis alignment, and control logic. These tools allow researchers to evaluate numerous design scenarios simultaneously, considering not only thermal efficiency but also cost, durability, and environmental indicators.

3.5. Discussion of Research Trends

The body of literature indicates a clear shift toward simplified, adaptive, and sensor-assisted tracking solutions suitable for building-scale applications. Flat-plate and glass tube collectors equipped with low-energy, discrete tracking mechanisms provide a realistic pathway toward decarbonizing heating systems in regions with variable solar conditions [53].

However, challenges remain in terms of standardized testing procedures, dynamic modeling under mixed radiation, and integration with predictive control systems. Future work is expected to focus on intelligent algorithms capable of self-adjusting the rotation step based on historical data, short-term weather forecasts, and real-time performance feedback [50].

The next section provides an overview of emerging adaptive and intelligent tracking strategies, including sensor-based control, predictive algorithms, and machine-learning approaches that aim to further optimize energy use and system durability.

Overall, the evolution of stepwise tracking systems demonstrates a clear progression from purely geometric optimization toward dynamic, data-driven operation. While early research primarily focused on defining optimal rotation steps and axis orientation, more recent studies have highlighted the importance of control algorithms that can respond to rapidly changing solar and meteorological conditions. Traditional discrete tracking methods, although effective, remain limited by fixed movement schedules that cannot fully exploit variable irradiance or diffuse radiation patterns [74].

To further enhance performance, modern research increasingly integrates automation, sensors, and predictive control into solar thermal systems. Adaptive and intelligent tracking approaches—combining stepwise motion with real-time feedback and learning algorithms—represent the next stage in this development. These concepts are discussed in detail in the following section, which reviews recent advances in adaptive, sensor-based, and AI-assisted tracking strategies for flat-plate and glass-tube solar collectors.

Concentrating solar thermal collectors require precise tracking of the solar beam to maintain focus on the receiver surface. Their geometry and optical characteristics

determine both the achievable concentration ratio and the mechanical complexity of the tracking system.

As illustrated in Figure 5, single-axis systems such as parabolic troughs and linear Fresnel reflectors concentrate sunlight along a focal line, while dual-axis systems like parabolic dishes and heliostat fields focus radiation to a single point. The required tracking precision increases with the concentration ratio, influencing actuator design, energy consumption, and optical efficiency.

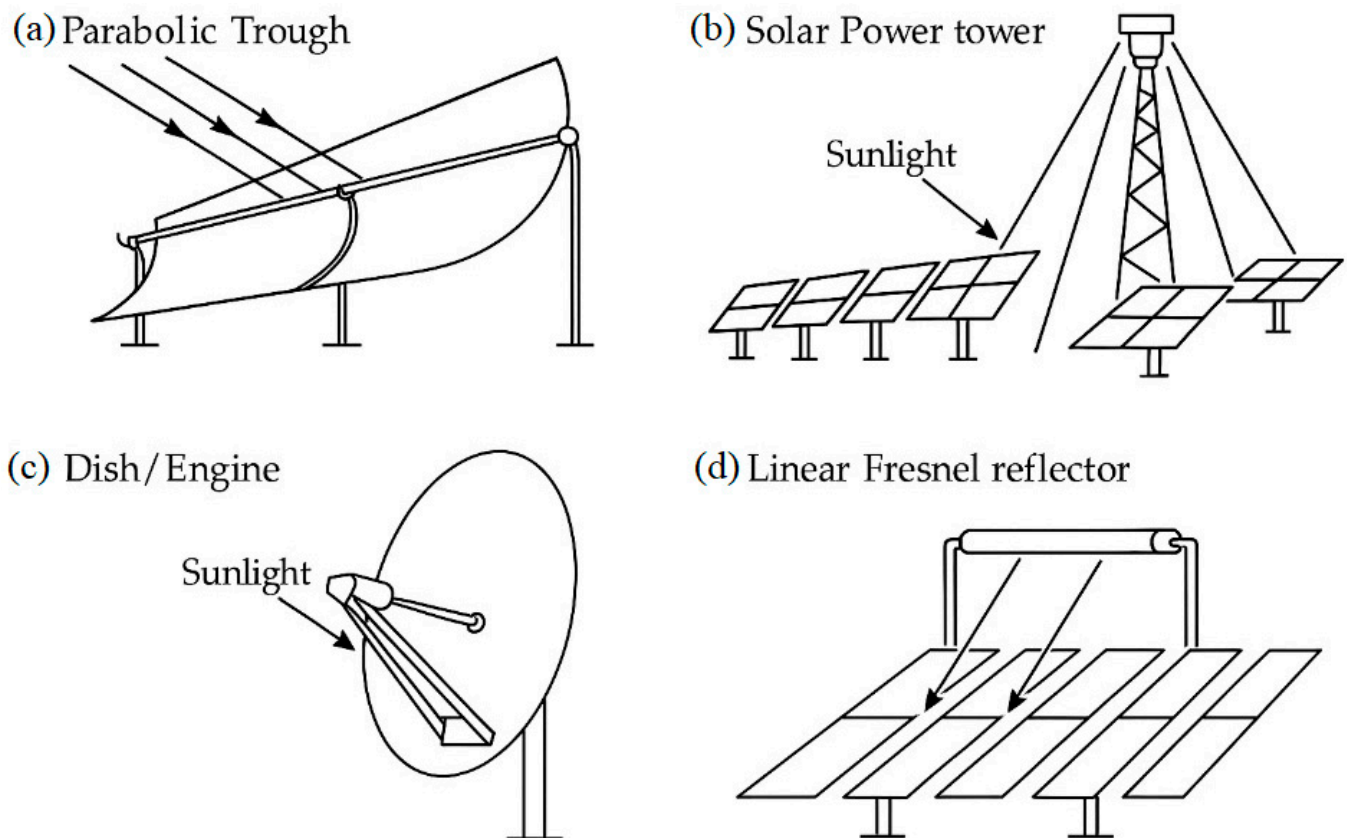


Figure 5. Representative examples of concentrating solar thermal collectors with single- and dual-axis tracking: (a) parabolic trough, (b) solar power tower, (c) parabolic dish, and (d) linear Fresnel reflector [75,76].

4. Adaptive and Intelligent Tracking Strategies

The development of adaptive and intelligent tracking systems has been driven by the need to improve solar thermal efficiency under fluctuating weather conditions while keeping energy consumption and mechanical wear to a minimum. Conventional stepwise tracking systems operate according to predefined rotation schedules, which are effective during clear-sky periods but less optimal when diffuse radiation dominates or when solar intensity changes rapidly [77]. Adaptive and intelligent tracking concepts aim to overcome these limitations by employing control algorithms that respond to real-time environmental inputs and continuously optimize collector orientation [78].

4.1. Concept of Adaptive Tracking

Adaptive tracking systems adjust their rotation step size, update frequency, or activation threshold according to environmental data such as solar irradiance, beam-to-diffuse ratio, or collector outlet temperature [79]. Rather than performing regular movements, they react to specific conditions—for instance, when the reduction in captured radiation exceeds

a defined limit. This strategy prevents unnecessary mechanical motion during cloudy or low-radiation periods, preserving both energy efficiency and system durability [80].

Two main adaptive principles are often applied. The first is angle-based adaptation, where the collector moves only if the incidence angle error exceeds a given threshold (typically 2–3°) [81]. The second is irradiance-based adaptation, in which the controller reacts when measured beam radiation drops by a defined percentage (e.g., 5–10%) [81]. These simple rules have proven to significantly extend actuator lifetime without notable loss of solar energy capture.

Hybrid configurations go further by combining real-time monitoring with short-term meteorological forecasting or empirical irradiance models, allowing the controller to anticipate cloud movement and adjust orientation proactively. This predictive capability is becoming increasingly accessible thanks to open-source weather APIs and on-site solar monitoring networks.

4.2. Sensor-Based and Feedback Control Systems

In contrast to algorithmic or open-loop tracking, sensor-based systems rely on direct feedback from optical or thermal sensors to achieve precise solar alignment. Common solutions use pairs of photodiodes or light-dependent resistors (LDRs) separated by a small shading barrier, producing voltage differences proportional to solar displacement [80,81]. The controller interprets these signals to reorient the collector until the readings are balanced.

Sensor-based closed-loop control provides excellent angular accuracy—often better than 1°—but requires careful calibration and periodic maintenance. Contamination, dust, or shading can introduce errors in measurement, leading to misalignment if not corrected. To mitigate such issues, hybrid feedback systems are now commonly employed: open-loop algorithms handle regular motion, while sensor feedback fine-tunes orientation when deviations occur [82].

More recently, wireless sensor networks (WSNs) have been applied to coordinate the movement of multiple collectors within the same installation. By sharing irradiance and temperature data, each unit can operate in a cooperative mode, improving system-wide efficiency and reducing redundant movement—an especially valuable feature for building-integrated solar thermal systems (BISTs) [83].

4.3. Intelligent Control and Machine Learning Applications

The intersection of solar thermal engineering with artificial intelligence (AI) and machine learning (ML) has opened new directions in system control. Intelligent algorithms can learn optimal tracking patterns from historical data and continuously refine their decision-making process based on real-world feedback [84].

Typical AI-based techniques include:

- ✓ Fuzzy Logic Controllers (FLCs), which use human-like reasoning through linguistic rules (e.g., “if irradiance drops rapidly and collector output decreases, then rotate by 5°”) [85];
- ✓ Artificial Neural Networks (ANNs), capable of predicting optimal collector orientation from prior irradiance and temperature datasets [86];
- ✓ Model Predictive Control (MPC), which integrates real-time optimization and short-term weather forecasts to schedule tracking movements efficiently [87].

These intelligent controllers have demonstrated remarkable potential in conditions with frequent irradiance fluctuations. Experiments show that FLC-based systems can reduce the number of rotations by 30–40% while retaining over 95% of the available energy gain. Neural network models trained on one climatic season have successfully

predicted optimal daily rotation patterns for the following year, reducing the need for manual parameter tuning [88].

When combined with Internet of Things (IoT) architectures, such controllers form part of a new generation of smart solar thermal systems. Real-time data from sensors are transmitted to cloud-based platforms, where algorithms continuously update control parameters and issue remote adjustments [89]. This integration supports predictive maintenance, remote diagnostics, and data-driven optimization of thermal performance.

4.4. Integration with Building Energy Management Systems (BEMS)

In the context of modern building design, adaptive tracking is increasingly being integrated with Building Energy Management Systems (BEMS). These systems coordinate solar heat generation with other subsystems—such as heat pumps, storage tanks, and ventilation units—ensuring optimal energy use across the entire building [90].

When the heat demand is low or the storage tank is fully charged, the BEMS may temporarily pause collector tracking to prevent overheating or unnecessary mechanical motion. Conversely, during high-demand periods, predictive control can preemptively adjust the collector position to maximize energy availability. Such coordinated operation allows not only improved efficiency but also a reduction in cycling losses and actuator wear [91].

By combining adaptive tracking with predictive load management, BEMS-based solutions transform solar collectors into active components of smart building infrastructure, capable of responding both to environmental and operational conditions [92].

4.5. Future Perspectives

Adaptive and intelligent tracking strategies are gradually redefining the concept of solar thermal collection—from static energy devices to autonomous, learning systems capable of continuous optimization. The current trend points toward greater integration with AI-driven predictive control, digital twin modeling, and self-calibrating algorithms that minimize the need for manual intervention.

However, several research challenges remain. These include the standardization of control protocols, the cybersecurity of networked tracking systems, and the validation of AI-based algorithms under real climatic variability. A holistic approach combining control intelligence, life-cycle sustainability, and cost optimization will be crucial for the next generation of solar thermal technologies.

The increasing role of adaptive and intelligent control has also reshaped how the performance of solar thermal collectors is evaluated. While traditional studies focused mainly on optical geometry and radiation capture, current research highlights the influence of diffuse radiation, collector geometry, and transient sky conditions on overall system efficiency. Understanding how adaptive and stepwise tracking systems perform under cloudy or partially diffuse conditions is essential for assessing their practical benefits.

The next section therefore examines the thermal and optical performance of glass-tube and flat-plate solar collectors, with a particular focus on cloudy-sky operation, diffuse radiation contribution, and experimental validation under real-world climatic conditions.

5. Glass Tube Collectors and Cloudy-Sky Performance

The optical and thermal behavior of solar collectors strongly depends on their geometry and the prevailing sky conditions. Under clear-sky circumstances, beam radiation dominates, and precise solar alignment through tracking leads to significant energy gains. However, in many temperate and continental regions, diffuse radiation can account for 30–60% of total solar input, particularly during spring and autumn months [93]. In such

environments, the design of the collector—its geometry, optical coating, and insulation—becomes just as important as its tracking strategy.

5.1. Optical Characteristics and Structural Configuration

Glass-tube collectors (GTCs), often referred to as evacuated tube collectors (ETCs), differ fundamentally from flat-plate collectors (FPCs) in both construction and optical behavior. Each tube consists of a cylindrical glass envelope enclosing an absorber coated with a selective layer, typically with a vacuum gap between the two surfaces to minimize convective losses [82]. This geometry allows for efficient absorption of radiation from a wide range of incident angles, making GTCs less sensitive to misalignment and more effective under partially cloudy conditions [68].

In contrast, flat-plate collectors rely on planar absorbers positioned beneath a transparent cover plate. Their optical efficiency is highest when solar rays strike the surface nearly perpendicular, and it declines rapidly as the incidence angle increases [83]. As a result, the performance of FPCs can vary significantly throughout the day, especially in installations without tracking or with large angular steps.

The circular cross-section of GTCs provides a natural advantage in capturing diffuse and oblique radiation, as parts of the cylindrical surface are always oriented favorably toward the Nešović [68]. Moreover, the use of vacuum insulation greatly reduces heat loss at high operating temperatures, making these systems suitable for climates with cold or windy conditions.

5.2. Response to Diffuse and Variable Radiation

One of the key challenges in solar thermal engineering is quantifying collector performance under non-uniform irradiance, such as cloudy-sky or mixed conditions. While beam radiation can be accurately modeled through geometric projection, diffuse radiation requires angular integration over the entire sky dome [68].

Experimental and numerical studies have consistently shown that GTCs outperform FPCs during periods dominated by diffuse radiation. Tabarhoseini et al. (2022) reported that under cloudy conditions, the energy yield of an evacuated tube collector exceeded that of a fixed flat-plate collector by 25–30% [94].

The geometry of glass tubes reduces the dependence of thermal efficiency on the incidence angle modifier (IAM). This means that while FPCs experience sharp performance drops during early morning and late afternoon hours, GTCs maintain stable efficiency throughout the day—even without precise tracking [68]. Such behavior is particularly advantageous for stepwise or adaptive tracking systems, which do not continuously follow the Sun but still benefit from the tube's omni-directional optical properties.

5.3. Experimental Results Under Cloudy-Sky Conditions

Recent experimental work has provided valuable insight into how glass-tube collectors respond to transient irradiance and diffuse light. Kowalik and Nešović conducted comparative field tests between a relative single-axis tracking glass-tube collector (rSAT-GTC) and a fixed flat-plate collector (FPC) under both clear and cloudy conditions [67].

Their findings revealed that during clear-sky days, the rSAT-GTC achieved up to 35% higher daily energy gain than the FPC. However, under fully cloudy or mixed-sky conditions, the relative advantage decreased to approximately 10–15%, highlighting the diminishing role of active tracking when diffuse radiation dominates. The study also confirmed that even without tracking, the GTC maintained higher instantaneous efficiency due to lower convective and radiative losses.

Measurements indicated that under diffuse-dominant conditions (beam-to-diffuse ratio < 0.4), the incidence angle modifier (IAM) of the GTC remained above 0.95, compared

to about 0.75 for the FPC. This explains the stability of GTC performance across varying weather conditions and reinforces the suitability of these systems for Central European climates, where cloudy-sky operation is frequent.

5.4. Comparative Performance Evaluation

Comparative analyses indicate that while tracking improves overall radiation capture, the marginal gains of continuous tracking for GTCs are smaller than for FPCs, owing to the tube's inherent angular acceptance. In practice, the optimal configuration for continental or mixed climates often combines stepwise or adaptive tracking with glass-tube collectors, balancing performance and simplicity [68].

A meta-analysis of over 20 experimental and numerical studies shows that, on an annual basis:

- ✓ Fixed FPC systems achieve mean thermal efficiencies of 40–50%,
- ✓ Stepwise-tracking FPCs reach 50–60%,
- ✓ Fixed GTCs operate in the range of 55–65%, and
- ✓ Stepwise or adaptive GTCs achieve 60–70%, depending on local climate and load profile [68].

These results underline the importance of selecting collector geometry and tracking strategy as complementary design parameters, rather than independent choices. The combination of cylindrical absorber geometry and limited-angle tracking provides an effective balance between high optical performance and mechanical simplicity [68].

5.5. Design Implications and Research Perspectives

The evidence gathered from both simulations and experiments suggests that glass-tube collectors equipped with adaptive or stepwise tracking offer one of the most technically and economically balanced solutions for mid-latitude regions. Their capability to maintain stable output under diffuse light, coupled with low thermal losses, makes them ideal for integration into residential, educational, and public buildings with variable heat demand [95].

Nevertheless, several research gaps remain. The standardization of diffuse radiation testing procedures is still lacking, and differences in IAM characterization among laboratories complicate the comparison of results. Furthermore, the dynamic interaction between tracking control and diffuse radiation fields remains insufficiently explored. High-resolution monitoring of irradiance components and sky luminance distributions could significantly improve model calibration and energy yield prediction.

Ongoing work should therefore aim to develop unified optical–thermal models that couple adaptive tracking algorithms with diffuse sky models (e.g., Perez or Hay–Davies distributions). Such models will be essential for accurately predicting system performance across the full range of realistic weather conditions [96].

The comparative analysis of glass-tube and flat-plate collectors under cloudy-sky conditions demonstrates that system performance depends not only on tracking strategy but also on the collector's geometry and optical acceptance. To quantify these relationships more precisely, a detailed examination of thermal and optical modeling approaches is required. The next section presents recent developments in energy yield simulation and optical characterization of solar thermal collectors, focusing on the integration of adaptive tracking control within dynamic performance models.

6. Thermal and Optical Modeling of Adaptive Tracking Systems

The modeling of adaptive and stepwise tracking collectors combines optical analysis, thermal balance, and control logic, forming a multi-domain problem that links radiation geometry with transient heat transfer. Reliable prediction of performance requires ac-

counting for the dynamic interaction between the Sun's position, collector orientation, and environmental boundary conditions [97].

6.1. Fundamentals of Optical Modeling

The optical efficiency of a solar collector defines the fraction of incident radiation effectively absorbed by the collector surface. For flat-plate collectors (FPCs), the dependence of transmittance and absorptance on the incidence angle θ is usually expressed by the incidence angle modifier (IAM) function:

$$IAM_{FPC}(\theta) = 1 - b_0 \left(\frac{1}{\cos \theta - 1} \right) \quad (1)$$

where b_0 is an empirical correction factor ranging typically between 0.08 and 0.15 depending on the glazing material and absorber finish [98].

For glass-tube collectors (GTCs), the analysis is more complex because of the cylindrical absorber geometry. Optical efficiency depends on both the axial (θ_a) and transversal (θ_t) angles of incidence:

$$IAM_{GTC}(\theta_a, \theta_t) = f(\cos \theta_a, \cos \theta_t) \quad (2)$$

Integration of absorbed irradiance over the tube circumference shows that GTCs maintain higher optical gains at oblique incidence, which explains their superior performance under diffuse or partly cloudy conditions [68].

In adaptive tracking studies, the instantaneous absorbed solar power is calculated as:

$$Q_{sol} = G_T (\tau\alpha)_{eff} IAM(\theta) \quad (3)$$

where G_T —total solar irradiance incident on the collector plane, $(\tau\alpha)_{eff}$ —effective transmittance–absorptance product [99].

6.2. Thermal Balance and Collector Efficiency

The thermal behavior of solar collectors is governed by the Hottel–Whillier–Bliss equation, which relates useful heat output to absorbed radiation and heat losses [100]:

$$\eta = \eta_0 - a_1 \frac{(T_m - T_a)}{G_t} - a_2 \frac{(T_m - T_a)^2}{G_t} \quad (4)$$

where η_0 —optical efficiency at normal incidence, a_1 and a_2 —heat-loss coefficients, T_m —mean fluid temperature, T_a —ambient temperature.

For adaptive tracking systems, both the irradiance G_T and the incidence angle θ become time-dependent variables. The total useful heat gain over a given period can therefore be written as:

$$Q_u = \int \eta(t) G_T(t) A_c dt \quad (5)$$

where A_c —collector aperture area [95].

Dynamic simulations indicate that efficiency variations caused by collector rotation or short-term shading can be significant, especially when actuator motion interrupts steady-state heat transfer. To capture these transients, finite-difference or lumped-capacity thermal models are commonly applied [101].

6.3. Simulation Tools and Modeling Approaches

Several numerical platforms have been developed for coupled optical–thermal simulations of tracking collectors.

- ✓ TRNSYS provides modular components for solar geometry, radiation processing, and thermal performance, enabling long-term energy yield simulations for stepwise and adaptive configurations [102].
- ✓ EnergyPlus includes integrated sky models (Perez, Hay–Davies) that allow evaluation of diffuse radiation contributions on tilted or moving surfaces [103].
- ✓ MATLAB/Simulink environments are often used to design and test control algorithms, allowing direct coupling between actuator dynamics and collector heat balance [104].
- ✓ BISTRA and similar research-grade tools specialize in façade-integrated collectors, offering detailed treatment of view factors and diffuse radiation exchange [105].

These simulation platforms enable researchers to evaluate the influence of rotation step, control logic, and climatic input on daily or seasonal collector performance. Comparative studies show that adaptive tracking models generally predict 20–30% higher annual thermal gains than fixed installations under continental or temperate climatic conditions, depending on the local beam-to-diffuse ratio.

6.4. Model Validation and Sensitivity Analysis

Validation of numerical results against experimental or benchmark data is crucial for ensuring model reliability. Studies comparing simulated and measured energy yields typically report deviations of 5–10%, depending on measurement accuracy and weather variability. Key parameters influencing model sensitivity include:

- ✓ the incidence-angle coefficient b_0 ,
- ✓ the effective transmittance–absorptance product $(\tau\alpha)_{eff}$,
- ✓ the collector tilt angle β ,
- ✓ the diffuse-to-beam ratio input from meteorological data.

Uncertainty analyses—often using Monte Carlo or Latin Hypercube Sampling methods—show that the combined optical and meteorological uncertainties contribute less than 5% to annual yield estimation when properly characterized.

6.5. Modeling Limitations and Research Perspectives

Despite the progress achieved, several simplifications remain inherent in current modeling practice. Many models assume uniform irradiance distribution across the collector surface and neglect edge effects or shading from support structures. For cylindrical collectors, the diffuse-radiation treatment is often approximated, leading to discrepancies under heavily overcast skies.

Recent research trends point toward coupled optical–control simulations, where the tracking algorithm directly modifies the instantaneous incidence angle in the optical sub-model. Advanced ray-tracing techniques and Monte Carlo radiation models are increasingly being integrated with thermal solvers to capture non-uniform flux distributions. Emerging approaches based on digital twins and machine-learning-assisted parameter calibration show promise in improving model fidelity and enabling near real-time performance prediction.

Future work should focus on developing unified frameworks that link adaptive control algorithms with both beam and diffuse radiation models, providing more accurate representation of real-world operation under variable sky conditions.

The combined optical–thermal modeling framework outlined above provides the foundation for evaluating the practical benefits of adaptive and stepwise tracking. By integrating control dynamics with heat-transfer equations, these models make it possible to predict seasonal energy yield and assess system performance across diverse climates and operating conditions. The next section examines how these modeling insights translate into

energy yield evaluation and techno-economic performance, focusing on cost effectiveness, payback time, and the broader implications for renewable heat integration in buildings.

7. Energy Yield and Techno-Economic Evaluation

The performance assessment of solar thermal technologies must consider both thermal efficiency and long-term economic viability. While adaptive and stepwise tracking systems offer measurable increases in energy yield, they also introduce additional investment and operational costs. A balanced evaluation therefore requires integrating energetic, economic, and environmental indicators to determine whether the added complexity leads to a net benefit over the system's lifetime [106].

7.1. Seasonal and Annual Energy Yield

The annual energy yield Q_{annual} expresses the total useful heat delivered by the collector over a full year:

$$Q_{annual} = \int_0^{8760h} \eta(t) G_T(t) A_c dt \quad (6)$$

where $\eta(t)$ —instantaneous thermal efficiency, $G_T(t)$ —total irradiance on the collector surface, A_c —aperture area [106].

Comparative studies indicate that stepwise tracking generally increases annual energy yield by 20–30%, whereas adaptive tracking can achieve improvements of 30–35% compared with fixed systems under mid-latitude conditions [107]. These gains depend on the local beam-to-diffuse ratio, collector geometry, and the rotation step size (ψ). Systems with $\psi = 10$ – 15° typically achieve near-optimal performance while maintaining low actuator use [107].

7.2. Performance and Cost Indicators

To provide a complete picture of system effectiveness, several key indicators are commonly used:

Levelized Cost of Heat (LCOH)—representing the discounted cost of useful heat produced over the lifetime of the installation [108]:

$$LCOH = \frac{\sum_{t=1}^n \frac{C_t + O_t}{(1+r)^t}}{\sum_{t=1}^n \frac{Q_{u,t}}{(1+r)^t}} \quad (7)$$

where C_t —denotes capital expenditure, O_t —operational and maintenance cost, $Q_{u,t}$ —useful heat in year t , r —discount rate, n —system lifetime.

Tracking Efficiency Index (TEI)—indicating the ratio between additional useful heat and actuator energy consumption [109]:

$$TEI = \frac{Q_{gain}}{E_{act}} \quad (8)$$

Values above 200–300 are typical for adaptive systems, confirming that the energy gained vastly exceeds the energy used for motion [109].

Energy Payback Time (EPBT) and Simple Payback Period (SPB)—quantifying the time required for energy and financial return [110].

Typical parameter ranges for various system configurations are summarized in Table 3, based on consolidated data from recent literature.

Table 3. Summary of techno-economic indicators for different collector and tracking configurations [9,64,111].

System Type	Typical Annual Gain vs. Fixed FPC [%]	TEI [–]	EPBT [Years]	LCOH Reduction [%]	Maintenance Frequency [1/Year]
Fixed FPC	0	–	2.5–3.0	baseline	low
Stepwise FPC	+20–25	150–200	2.0–2.5	5–10	low
Adaptive FPC	+30–35	200–300	1.8–2.3	10–15	low
Fixed GTC	+10–15	–	1.7–2.2	≈5	low
Adaptive GTC	+30–40	250–350	1.5–2.0	12–18	low–medium

7.3. Economic Implications of Tracking

Introducing tracking mechanisms increases capital cost (CAPEX) by roughly 10–20% compared with fixed collectors [112]. However, higher annual heat output compensates for this cost within a few operating years. Across European climates, adaptive tracking typically lowers the LCOH by 8–15%, particularly in regions with variable solar conditions. The cost advantage is more pronounced when solar heat replaces high-cost fuels such as natural gas or electricity.

Operation and maintenance costs remain low for stepwise configurations due to limited actuator cycles. Continuous dual-axis systems, on the other hand, may face higher wear and servicing needs. Adaptive controllers that pause movement during periods of low irradiance can reduce actuator operation by 60–70%, extending component lifetime and improving system reliability.

7.4. Regional Impact and Financial Incentives

The techno-economic indicators presented above were evaluated under baseline market conditions; however, the actual economic performance of solar thermal systems strongly depends on regional policy frameworks. In regions offering investment subsidies or tax reductions—such as EU Member States under the Green Deal framework or Asian countries implementing renewable heat incentives—the Levelized Cost of Heat (LCOH) can be substantially reduced. A sensitivity analysis indicates that a 20–30% subsidy on the initial capital cost typically lowers LCOH by 12–18%, thus shortening the payback period of adaptive and stepwise tracking systems. These findings highlight the importance of financial mechanisms in enhancing the competitiveness and large-scale deployment potential of advanced solar tracking technologies.

7.5. Integration with Energy Policy and Building Standards

From a regulatory and sustainability perspective, adaptive tracking supports compliance with the Energy Performance of Buildings Directive (EPBD) and national nZEB requirements [113]. By enhancing the solar fraction in domestic hot-water or space-heating systems, it contributes to lower primary energy demand and reduced greenhouse-gas emissions.

In building-integrated solar thermal (BIST) applications, intelligent tracking allows dynamic adjustment of heat generation to match real-time demand, improving load coverage and comfort. Such integration with Building Energy Management Systems (BEMS) enables coordinated operation with auxiliary systems like heat pumps or district heating exchangers [114]. This synergy results in shorter payback times and stronger alignment with decarbonization goals.

7.6. Energy Payback and Environmental Performance

Environmental indicators such as EPBT and carbon payback time (CPBT) provide complementary sustainability insights. For modern collectors, EPBT typically ranges from 1.5 to 3 years, depending on manufacturing energy intensity and local irradiance [115]. Adaptive tracking can shorten this period by about 0.3–0.5 years while reducing the carbon payback time to less than two years [116].

These results confirm that moderate tracking complexity not only improves energy yield but also accelerates environmental benefits, supporting the transition to low-carbon heating technologies [117].

7.7. Discussion and Implications

The techno-economic comparison summarized in Table 2 highlights that stepwise and adaptive tracking systems achieve a strong balance between performance and cost. While continuous tracking remains advantageous for large-scale or industrial applications, its complexity and higher OPEX limit its relevance in small or medium building systems.

Adaptive strategies offer a pragmatic alternative: they capture most of the additional radiation potential while maintaining low mechanical and control requirements. Under typical European conditions, such systems achieve economic parity within 5–7 years, well within the expected service life of 20–25 years [116]. Consequently, adaptive tracking can be regarded as a mature, cost-effective, and sustainable enhancement for future solar thermal installations.

The energy and cost analyses presented in this section demonstrate that adaptive and stepwise tracking technologies deliver tangible performance gains with limited financial penalties. To ensure their widespread adoption, future research should focus on technological standardization, predictive control optimization, and durability improvement. These aspects form the basis of the next section, which outlines emerging research trends and challenges in the development of intelligent solar thermal systems.

8. Future Directions and Research Challenges

The future development of solar tracking systems for flat-plate and tubular collectors will focus on improving structural reliability, control intelligence, and cost efficiency. Mechanically, lightweight and corrosion-resistant composite materials are expected to replace traditional steel frames, reducing fatigue and extending service life under cyclic loading. From a technological perspective, the integration of IoT sensors, digital twins, and AI-based predictive control will enable self-learning systems capable of real-time optimization under variable solar and weather conditions. Further improvements in energy storage coupling (e.g., with phase-change materials or thermochemical storage) will allow continuous operation during low-irradiance periods. Economically, progress will depend on lowering actuator and sensor costs and leveraging regional subsidies and carbon-credit mechanisms to enhance the economic feasibility of adaptive tracking installations. Finally, long-term durability and maintenance strategies—such as remote diagnostics and fault prediction—will become essential to guarantee stable energy yield and minimize the life-cycle environmental impact of tracking systems. Future research should therefore combine material testing, predictive modeling, and techno-economic optimization to ensure the sustainable large-scale implementation of next-generation solar tracking technologies.

In addition to advancements in control and predictive algorithms, further research should focus on hardware and material innovation in collector and tracking system design. Future collector technologies are expected to utilize selective absorber coatings with higher spectral stability, anti-reflective glass layers, and composite frame materials that improve thermal efficiency while reducing structural fatigue. For tracking systems, next-generation

lightweight actuators, low-friction bearings, and adaptive mount geometries can significantly enhance reliability and reduce maintenance costs. These hardware improvements, when combined with intelligent control and predictive maintenance, will drive the next stage of development toward high-efficiency and low-cost solar thermal systems.

8.1. Integration of Artificial Intelligence and Predictive Control

The use of artificial intelligence (AI) and machine learning (ML) in solar thermal applications is expanding rapidly. Intelligent controllers are capable of predicting solar irradiance, adjusting collector orientation, and scheduling operation based on weather forecasts or building heat demand [10].

Recent studies highlight the role of fuzzy logic, neural networks, and model predictive control (MPC) in enhancing the responsiveness of solar tracking systems under variable sky conditions [116]. However, the main challenge lies in generalizing models trained under specific climatic or operational conditions. Transfer learning, adaptive re-training, and hybrid control approaches are emerging as promising solutions to improve model robustness.

The future direction of research should therefore emphasize AI-assisted optimization frameworks, integrating real-time meteorological data, actuator feedback, and energy storage state. Such systems could evolve toward fully autonomous solar thermal plants, capable of continuous self-calibration and performance learning.

8.2. Durability, Reliability, and Maintenance Optimization

Mechanical reliability remains one of the key concerns in the long-term operation of tracking systems. Even moderate actuator wear or sensor misalignment can reduce overall system efficiency and increase maintenance costs. Future design strategies should aim to minimize moving parts through the use of magnetically coupled actuators, solid-state positioning systems, and shape-memory materials for motion control.

The development of predictive maintenance algorithms based on vibration, temperature, or electrical feedback signals offers a path toward early fault detection. By combining IoT-based sensors with cloud analytics, operators could transition from reactive to proactive system management, extending component lifetime and reducing lifecycle costs.

8.3. Standardization and Modeling Harmonization

Despite extensive research, the lack of standardized testing protocols for adaptive and stepwise tracking collectors remains a major barrier to their wider adoption. Existing standards such as EN 12975 or ISO 9806 were developed primarily for fixed systems and do not account for intermittent motion or time-dependent incidence angle effects [117,118].

Future revisions of these standards should include dynamic test sequences, actuator performance criteria, and diffuse-radiation sensitivity analyses. Additionally, harmonization of modeling methods is needed—particularly regarding diffuse radiation treatment and incidence angle modifier (IAM) parameterization. Establishing benchmark datasets and shared simulation frameworks could significantly enhance comparability and reproducibility of results.

8.4. Hybrid and Multifunctional Systems

The integration of solar thermal collectors with other renewable technologies opens new research pathways. Photovoltaic-thermal (PVT) systems with adaptive tracking can simultaneously produce electricity and heat, optimizing total solar energy utilization. Similarly, coupling collectors with heat pumps, thermal storage tanks, or phase-change materials (PCM) can stabilize heat supply and increase the overall renewable share in building energy systems [119].

These hybrid configurations require coordinated control between subsystems, achievable through Building Energy Management Systems (BEMS) or district-level energy platforms. Adaptive tracking data can inform heat demand forecasting, load shifting, and real-time optimization of energy flows.

8.5. Sustainability and Circular Design

Sustainability concerns extend beyond operational performance to include embodied energy, recyclability, and material recovery. Future research should therefore focus on low-impact manufacturing methods, lightweight absorber designs, and the use of recyclable or bio-based materials. Lifecycle assessment (LCA) frameworks specifically tailored for adaptive solar thermal systems are needed to capture the environmental trade-offs between added mechanical complexity and improved energy performance [120].

Furthermore, as collector systems become more intelligent and interconnected, cybersecurity and data privacy will emerge as new dimensions of sustainability, particularly in smart building networks.

8.6. Broader Research Outlook

The next generation of solar thermal systems will be defined by the convergence of AI-driven control, integrated energy modeling, and resilient design principles. Achieving this vision will require cross-disciplinary collaboration between mechanical engineers, computer scientists, and building physicists. Future projects should prioritize the development of open-source control platforms, shared irradiance datasets, and digital twins for system simulation and validation under real climatic variability.

As the global energy transition accelerates, adaptive and intelligent tracking collectors can play a central role in decarbonizing heat supply for buildings, especially in regions with moderate or variable solar resources.

The discussed research directions demonstrate that the future of solar thermal technology lies in intelligent, connected, and sustainable systems. Combining advanced control algorithms with durable mechanical design and standardized testing will be essential to unlock their full potential. The following conclusions summarize the key insights derived from this review and highlight the main contributions of adaptive tracking to the ongoing energy transition.

8.7. Engineering and Implementation Challenges

Despite the clear energetic and economic advantages of adaptive and stepwise tracking, several engineering barriers still hinder their large-scale deployment. The structural stability of moving collector systems remains a critical issue, especially under high wind loads or cyclic mechanical stresses that can lead to frame deformation and bearing wear. The fatigue and corrosion of joints, actuators, and support elements often shorten the service life of outdoor installations, particularly in humid or coastal climates. In addition, sensor drift and electronic degradation can reduce control accuracy over time, directly affecting energy yield and operational reliability. Maintenance frequency, dust accumulation on optical sensors, and alignment errors introduce further performance losses if not regularly corrected. Long-term degradation of absorber coatings and glazing materials under UV exposure also influences thermal efficiency and should be included in predictive performance models. Addressing these challenges will require robust materials, modular actuator designs, and the integration of predictive maintenance and remote diagnostics to ensure reliable operation and sustainable lifecycle performance of future solar tracking systems.

9. Conclusions

This review has analyzed the development, modeling, and practical implementation of adaptive and stepwise tracking systems for solar thermal collectors, emphasizing their role in the decarbonization of the building sector. The results of the literature synthesis indicate that moderate tracking complexity can deliver substantial energy and economic benefits without compromising system reliability.

Adaptive and stepwise tracking strategies increase annual heat yield by approximately 20–35% compared to fixed installations, depending on climatic conditions and collector geometry. When applied to both flat-plate and glass-tube configurations, these systems maintain high optical performance under diffuse and partially cloudy skies. The combination of discrete motion and intelligent control represents a practical alternative to continuous dual-axis tracking, achieving similar efficiency at significantly lower cost and mechanical wear.

From a techno-economic perspective, adaptive tracking reduces the levelized cost of heat (LCOH) by up to 15% and shortens the energy payback time (EPBT) by nearly half a year relative to conventional systems. These advantages, coupled with compatibility with Building Energy Management Systems (BEMS) and nZEB design principles, make adaptive solar thermal technology an important contributor to sustainable building decarbonization.

Future research should prioritize AI-assisted control, predictive maintenance, and standardization of dynamic testing methods, which are essential for large-scale implementation. The integration of solar thermal tracking with digital twins, hybrid PVT systems, and smart energy platforms will further enhance the role of these technologies in resilient, low-carbon building infrastructures.

In conclusion, adaptive and intelligent tracking systems are poised to redefine the performance boundaries of solar thermal energy. By combining data-driven control with robust design and life-cycle sustainability, they offer a viable pathway toward achieving higher renewable heat penetration and accelerating the transition to climate-neutral buildings.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

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