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Research Article



Recent Advances in Concentrating Solar Collectors: Technologies, Design Optimization, and Performance Enhancement Strategies: A Review

[1]E. N. Eewayed
[1]*University of Wasit, College of Engineering, Department of Mechanical Engineering, Iraq*

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Abstract: Concentrating solar collectors can supply heat for a wide range of applications, from industrial heating and cooling to power generation and high-temperature chemical processes. The amount of useful thermal energy obtained, however, varies with the collector design, operating conditions, heat-transfer characteristics, and the way heat is managed within the system. Drawing on experimental and numerical studies, this review compares parabolic trough, linear Fresnel, parabolic dish, central receiver, and compound parabolic concentrator systems in terms of their optical and thermal performance, practical limitations, and suitability for different applications. The discussion covers thermal energy storage, phase change materials, nanofluids, receiver design, optical losses, material degradation, and economic constraints, considering both the difficulties involved and the available approaches to improving performance. The suitability of a collector depends on the conditions under which it is expected to operate. Temperature requirements, the solar resource at the installation site, and limitations imposed by the rest of the system all influence which technology is appropriate. As a result, a collector that performs well in one application may not be the right choice for another. Improvements in heat transfer and thermal storage may provide higher thermal output and greater flexibility in operation, although the additional costs, pressure losses, and maintenance requirements can limit their practical value. Questions concerning material durability, thermal management, and the reliability of control strategies still require attention, together with long-term techno-economic studies carried out under realistic operating conditions. Greater efficiency, reliability, and economic viability in concentrating solar thermal systems will depend on selecting technologies that meet the needs of a particular application and optimizing their integration within the system.

Corresponding Author:
E. N. Eewayed
University of Wasit, College of Engineering, Department of Mechanical Engineering, Iraq

Nomenclature

Symbol	Definition	SI unit
C_g	Geometrical concentration ratio	–
A_a	Collector aperture area	m^2
A_r	Absorber or receiver area	m^2
η_{opt}	Optical efficiency	–
η_{th}	Thermal efficiency	–
Q_{abs}	Solar power absorbed by the receiver	W
Q_u	Useful thermal power transferred to the working fluid	W
I_{DNI}	Direct normal irradiance	$W\ m^{-2}$
m	Mass flow rate of the working fluid	$kg\ s^{-1}$
c_p	Specific heat capacity of the working fluid	$J\ kg^{-1}\ K^{-1}$
T_{in}	Working fluid inlet temperature	K
T_{out}	Working fluid outlet temperature	K

Abbreviation	Definition	Abbreviation	Definition
CFD	Computational fluid dynamics	LHS	Latent heat storage
COP	Coefficient of performance	ORC	Organic Rankine cycle
CPC	Compound parabolic concentrator	PCM	Phase change material
CSP	Concentrating solar power	PDC	Parabolic dish collector
CSC	Concentrating solar collector	PEC	Performance evaluation criterion
CPVT	Concentrating photovoltaic–thermal	PTC	Parabolic trough collector
DNI	Direct normal irradiance	SHS	Sensible heat storage
HDH	Humidification–dehumidification	STC	Solar tower collector
HTF	Heat transfer fluid	TES	Thermal energy storage
LCOE	Levelized cost of electricity	XCPC	External compound parabolic concentrator
LFR	Linear Fresnel reflector		

INTRODUCTION

The continuing rise in global energy demand, linked to population growth, industrial expansion, and technological development, has raised concerns about the depletion of fossil fuel resources and the environmental consequences of their use. Renewable energy has consequently become increasingly important in efforts to strengthen energy security and reduce greenhouse gas emissions. Solar energy is one of the renewable resources capable of providing both heat and electricity. Its thermal applications extend from household water heating to industrial drying, desalination, process heating, and electricity generation[1,2]. Solar thermal collectors can be divided into two main categories: concentrating and non-concentrating systems. Non-concentrating collectors are mainly used where relatively low operating temperatures are sufficient. In CSCs, the mirrors collect sunlight across a relatively wide area and concentrate it onto a much smaller receiver. The higher solar flux achieved at the receiver provides the temperatures required for industrial applications and electricity production. Several technologies operate on this principle, including parabolic trough collectors (PTCs), linear Fresnel reflectors (LFRs), parabolic dish collectors (PDCs), and solar tower collectors (STCs). Although they share the same basic principle, their optical configurations, receiver designs and locations, and operating requirements are not the same. These differences determine, to a considerable extent, their thermal performance and the applications for which they are suitable[2,3]. The global distribution of direct normal irradiation (DNI), which represents the solar resource available to concentrating technologies, is presented in Figure 1[4].

Much of the recent work on CSCs has dealt with collector design and technological improvements intended to increase efficiency and reliability. Their performance is influenced by several connected factors: solar irradiance, optical properties, receiver geometry, heat transfer fluid (HTF) characteristics, operating temperature, and thermal losses. Studies in this area have addressed the arrangement of reflectors, the choice of tracking mechanisms, receiver configuration, and ways of controlling heat losses. Ray tracing and computational fluid dynamics (CFD), together with other analytical and numerical methods, are used to study the distribution of solar radiation, fluid flow, and heat transfer within collectors[3,5]. Several approaches have been considered to improve heat transfer within the receiver. Approaches include reshaping the absorber, fitting the receiver with fins or flow-disturbing inserts, and replacing conventional working fluids with advanced HTFs. Nanofluids can offer improvements in thermophysical properties and convective heat transfer, although the extent of these improvements varies with operating conditions. Higher viscosity, pressure drop, and pumping power may accompany these gains. Evaluating such modifications therefore requires attention to hydraulic and operational effects as well as the resulting heat transfer performance [5–7]. Thermal energy storage (TES) provides a means of dealing with fluctuations in solar energy supply. Heat

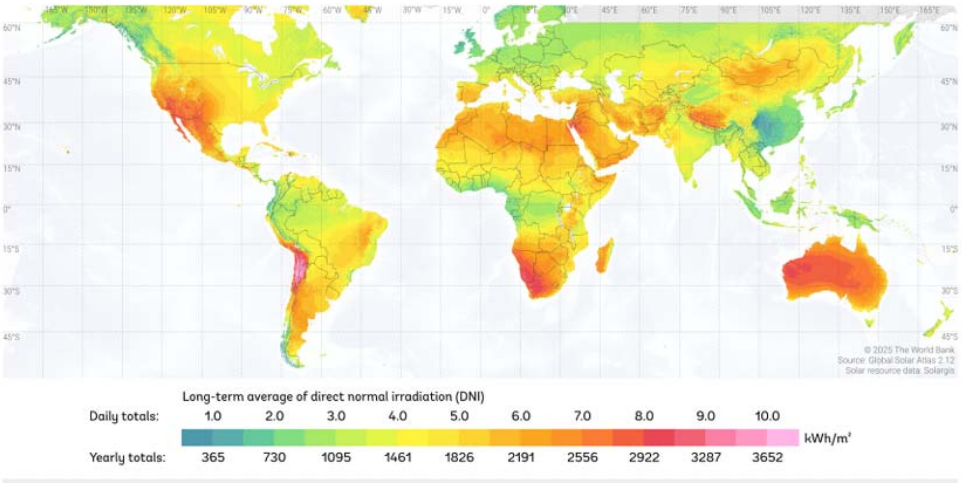


Figure 1: Global distribution of direct normal irradiation (DNI)

collected during periods of sufficient irradiation can be stored and used when solar input decreases or after sunset. Both sensible heat storage (SHS) and latent heat storage (LHS) using phase change materials (PCMs) can make heat delivery more stable and allow greater flexibility in system operation. Their performance, however, varies with the properties of the storage materials, heat transfer rates, operating temperatures, system configuration, and economic considerations. When TES is incorporated into a collector system, its design cannot be considered separately from that of the collector itself. The storage medium, operating conditions, and heat-delivery requirements all influence how effectively the integrated system performs. Storage capacity alone, therefore, does not provide a sufficient basis for judging the efficiency or reliability of the complete solar thermal system[2,8]. Although CSC technology has advanced considerably in recent years, its wider adoption continues to face technical and economic obstacles. Optical losses, heat losses from receivers, demanding tracking arrangements, material durability, and the costs of operation and maintenance remain important concerns. Some measures intended to improve optical or heat transfer performance can also make systems more expensive, increase hydraulic resistance, or complicate their construction. Judging the practical value of these measures requires examining optical and thermal performance together with system design, operating limitations, and economic feasibility, rather than treating efficiency improvements as sufficient evidence of technological competitiveness[3,5,7,8].

The present review considers recent developments in four major CSC technologies: PTCs, LFRs, PDCs, and STCs. The review addresses the operating principles, design features, and recent developments of these technologies, emphasizing optical configurations, receiver design, heat-transfer improvement, advanced working fluids, and TES integration. The review compares how these technologies perform in different applications, considering where their respective strengths and limitations become most apparent. It also discusses the technical obstacles that remain and the research needed to address them.

FUNDAMENTALS AND CLASSIFICATION OF CSCS

Working Principles of CSCs: In CSCs, the reflector assembly intercepts sunlight over a relatively large aperture and concentrates the collected radiation at the receiver, whose smaller surface area allows the solar energy to be absorbed more effectively. Concentrating the radiation in this manner increases the solar flux density compared with that of conventional non-concentrating collectors, allowing the system to reach higher operating temperatures. The receiver absorbs the concentrated energy and transfers it as heat to a HTF. The heat obtained can then be supplied to industrial processes, used for electricity generation, or applied in other thermal systems, depending on the collector configuration and its operating temperature[3]. Most CSC configurations are built around four principal components: the concentrator, the receiver, the supporting structure, and, where required, a solar tracking mechanism. The reflector assembly directs sunlight onto the receiver, where the absorbed radiation heats the circulating HTF. Throughout operation, the tracking system continuously corrects the collector's orientation to account for the Sun's changing position and maintain the required optical alignment. Without accurate alignment, part of the incoming radiation may miss its intended target or reach the receiver at an unfavorable angle. The tracking arrangement therefore depends on the geometry and optical characteristics of

the concentrator[9]. The amount of direct normal irradiation (DNI) available at an installation site also has a considerable effect on CSC performance. DNI is the solar irradiance measured on a surface perpendicular to the incoming solar rays. This distinction is important because conventional optical concentrators focus direct radiation, whereas diffuse radiation cannot be concentrated in the same way. For this reason, the location of the installation, atmospheric conditions, solar incidence angle, and tracking accuracy all affect the amount of solar energy collected. Regions receiving high DNI are generally better suited to concentrating solar applications. The useful heat obtained from the incoming radiation also depends on optical losses, the effectiveness of heat transfer to the working fluid, and heat escaping from the system to its surroundings[10].

Classification of CSCs: CSCs can be distinguished by their concentration geometry, tracking arrangements, and receiver configuration. CSCs are classified according to their focal geometry as either line-focus or point-focus systems. The focal arrangement distinguishes these collectors. In line-focus systems, the reflected rays form an elongated focal region along which a tubular receiver is installed. Point-focus collectors, in contrast, concentrate sunlight onto a localized focal area. This configuration permits higher concentration ratios and operating temperatures, but requires different structural arrangements and tracking mechanisms, which also determine their range of applications. Although both use line-focus geometry, PTCs and LFRs differ in reflector design. In a PTC, a single curved parabolic reflector rotates around one axis, directing the incoming radiation towards a tubular receiver positioned along its focal line. LFRs use several rows of flat or slightly curved mirrors, each with its own tracking mechanism, to reflect sunlight toward an elevated linear receiver. Their relatively simple reflector construction can reduce installation costs. However, shading between mirror rows, blocking of reflected radiation, and additional reflection losses can adversely affect their optical performance compared with PTCs[9,10]. The principal point-focus technologies are PDCs and STCs. A PDC uses a paraboloidal reflector to bring sunlight to a focal point, where the receiver is placed. Because the focal point moves with the Sun's position, PDCs require two-axis tracking to maintain the focus of reflected radiation on the receiver. In STCs, sunlight is collected by a field of individually controlled heliostats, each of which redirects the reflected beam towards a receiver positioned on a central tower. Heat absorbed at this receiver is transferred to a working fluid and subsequently used for electricity generation or other thermal applications. Compared with line-focus collectors, point-focus systems generally provide higher concentration ratios, although their tracking systems and receiver arrangements are usually more complex[9–11]. Compound parabolic concentrators (CPCs) belong to another group of concentrators based on non-imaging optics. They collect radiation arriving within a specified acceptance angle and can often operate with less demanding tracking arrangements. Since the present review concentrates on the four principal concentrating solar technologies, the discussion of CPCs is mainly limited to their role in receiver design and optical enhancement[2]. The main classifications of solar collectors are presented in Table 1.

Key Performance Parameters: The performance of CSCs is primarily assessed through geometrical, optical, and thermal parameters, particularly concentration ratio, optical efficiency, thermal efficiency, and useful thermal output. The values of these indicators differ from one collector design to another. Their comparison provides a basis for assessing collector performance, although the results are influenced by geometry, optical properties, operating conditions, and heat-transfer characteristics[2,3].

The geometrical concentration ratio (C_g) represents the collector aperture area (A_a) divided by the absorber or receiver area (A_r):

$$C_g = \frac{A_a}{A_r} \tag{1}$$

A high concentration ratio increases the solar energy flux incident on the receiver, allowing the collector to operate at higher temperatures. However, achieving these conditions requires accurate reflector alignment and continuous solar tracking, while thermal losses must be kept under control [9]. Optical efficiency quantifies how much of the solar power entering the collector aperture is ultimately absorbed by the receiver. The efficiency is calculated as follows:

$$\eta_{\text{opt}} = \frac{\dot{Q}_{\text{abs}}}{I_{\text{DNI}} A_a} \tag{2}$$

Here, denotes the solar power absorbed by the receiver (W), refers to the direct normal irradiance (DNI), and represents the collector aperture area (m²). Several optical factors govern this efficiency, notably mirror reflectivity, receiver absorptivity, tracking precision, and losses caused by shading and blocking. Surface imperfections and other optical deviations further reduce the radiation intercepted by the receiver and should therefore be considered in performance assessments[9].

Table 1: General classification of the main technologies for CSCs

Collector type	Concentration geometry	Typical tracking	Receiver configuration
PTC	Line-focus	Single-axis	Tubular receiver
LFR	Line-focus	Single-axis mirror tracking	Elevated linear receiver
PDC	Point-focus	Dual-axis	Focal-point receiver
STC	Point-focus	Dual-axis heliostats	Central tower receiver

Thermal efficiency (η_{th}) is defined as the ratio of useful thermal power transferred to the working fluid to the solar power incident on the collector aperture and is expressed as:

$$\eta_{\text{th}} = \frac{\dot{Q}_u}{I_{\text{DNI}} A_a} \quad (3)$$

The useful thermal power (Q_u) is calculated from the working fluid mass flow rate, specific heat capacity, and inlet–outlet temperature difference:

$$\dot{Q}_u = \dot{m} c_p (T_{\text{out}} - T_{\text{in}}) \quad (4)$$

where is the mass flow rate (kg/s), is the specific heat capacity (J/kg·K), and and are the inlet and outlet fluid temperatures, respectively. These expressions apply to steady-state conditions; for fluids with strongly temperature-dependent properties, useful thermal power is more accurately determined from the specific enthalpy difference[3]. Beyond optical and thermal efficiencies, collector performance is influenced by pressure drop, pumping power, heat losses, and operating temperature. Modifications to the receiver and measures intended to improve heat transfer can increase hydraulic resistance and the pumping power required. The temperature difference between the receiver and its surroundings is another important determinant of thermal losses, which generally increase as the receiver temperature rises relative to ambient conditions. Consequently, thermal efficiency alone cannot adequately characterize collector performance; optical losses, heat-transfer behavior, and the hydraulic requirements of fluid circulation must also be taken into account. Considered individually, thermal efficiency cannot fully describe the operating performance of a collector system[5].

The principles and performance indicators described above serve as a basis for examining technological developments and design changes in different CSC configurations. The next section discusses recent advances in the four principal technologies, with attention to the design features that distinguish them and their thermal and optical performance.

RECENT ADVANCES IN CSC TECHNOLOGIES

PTCs: PTCs are among the most mature concentrating solar technologies for medium- and high-temperature applications. In a PTC, the parabolic reflector follows the Sun through single-axis rotation, directing the concentrated radiation onto a tubular absorber along its focal line. Heat absorbed by the receiver is carried by the HTF to the application, where it can support industrial heating or electricity generation. Recent studies have explored alternative reflector arrangements and receiver configurations, seeking better thermal performance without incurring excessive heat losses or operating costs [12,13]. Figure 2 shows an experimental PTC field used in a solar-driven absorption cooling system[14].

Reflector geometry and receiver optimization remain central to PTC development. Conventional receivers generally have a metallic absorber tube surrounded by a transparent glass envelope. To reduce convective heat transfer, the space between the absorber tube and the surrounding glass envelope is evacuated. Recent efforts to improve PTC performance have addressed changes in reflector geometry, optical design, and receiver construction, with the aim of increasing solar energy absorption and improving thermal behavior. AbdelFatah et al.[12] reviewed different collector configurations and modeling approaches, examining aspects such as structural design, solar tracking, and methods for optimizing reflector geometry. They also pointed out the need for more accurate outlet-temperature predictions. The economic aspects of receiver technologies have been considered alongside these technical developments. Shokrnia et al.[13] investigated PTC and LFR configurations fitted with evacuated and non-evacuated receivers under different geographical conditions. The results show why improvements in thermal performance need to be examined together with implementation costs and operating conditions. Experimental work has also examined the use of PTCs in applications other than electricity generation. Galindo Luna et al.[14] investigated 15 PTCs with a total aperture area of approximately 38.4 m² integrated with an absorption cooling system. The collector field produced up to 6.5 kW of useful thermal power, with operating temperatures reaching 105 °C, showing its potential for solar-driven cooling. Work on



Figure 2: Experimental PTC field

PTC technology has largely focused on optical design, receiver improvements, and ways of operating the system more effectively. Despite the maturity of this technology, further work is needed to limit thermal losses, improve operational reliability, and reduce costs if PTCs are to be adopted more widely across solar thermal applications[12,13].

LFRs: LFRs are an alternative to PTCs, with a simpler optical design, a compact arrangement, and the possibility of lower construction and installation costs. In LFR systems, sunlight is reflected by rows of flat or slightly curved mirrors, each of which tracks the Sun independently. The reflected radiation is directed toward a stationary receiver located above the mirror field. Compared with conventional PTC designs, this arrangement requires less complex mechanical components. Recent investigations have focused on mirror geometry, sources of optical loss, and receiver performance, as well as the use of LFR technology in industrial heating and electricity generation[15]. Figure 3 shows an LFR installation at Harran University, Türkiye, including its main mirror field and elevated receiver.

The arrangement of mirrors within an LFR field has a direct effect on its optical performance. Mirror width, spacing, and inclination, together with the overall field layout, influence both optical efficiency and the distribution of solar flux. Grena[16] studied the geometric design of linear Fresnel concentrators, with particular attention to shading, blocking, and the loss of reflected radiation that fails to reach the receiver. Ray-tracing and quasi-analytical approaches have provided a means of comparing mirror configurations and evaluating their optical behavior while keeping computational demands relatively low. LFR receiver designs may incorporate secondary reflectors and protective enclosures to redirect radiation that would otherwise be lost and reduce heat dissipation from the receiver to the surrounding environment. Montanet et al.[17] investigated receiver heat losses in a commercial 9 MW electrical LFR power plant through experimental measurements and a simplified numerical thermal model. The model reproduced the measured losses with an uncertainty of approximately ±30%. Its predictions were nevertheless affected by wind conditions and receiver degradation, showing the limitations of simplified models when applied to large installations operating under changing environmental conditions. LFRs have also been studied for use in distributed energy systems. Yildirim and Aktacir[15] assessed an LFR–ORC configuration using experimental data from the collector and compared its technical, economic, and environmental performance with that of a photovoltaic system. Their results supported the use of LFR systems for small-scale electricity generation. However, economic limitations remain a barrier to its wider practical implementation. The comparison also showed the relevance of system integration and the intended application when assessing the practicality of such installations. Shading, blocking, incidence-angle effects, and heat losses at the receiver continue to restrict LFR performance. A simpler structure and lower initial construction costs do not, by themselves, ensure better economic results. Improvements in mirror-field layout and receiver configuration therefore need to be considered alongside optical efficiency, operating reliability, and project costs when assessing the practical performance of LFR systems[16,17].

PDCs: As point-focus concentrating systems, PDCs combine a modular configuration with the ability to reach high concentration ratios and operating temperatures.

They use paraboloidal reflectors with dual-axis solar tracking to direct sunlight toward a receiver positioned near the focal point. The temperatures reached by these systems allow their use in distributed power generation, industrial heating, and other applications requiring thermal energy. Work reported in recent years has addressed optical accuracy, receiver design, thermal management, and the integration of individual components, with the aim of improving system performance[18,19]. Figure 4 illustrates an experimental parabolic dish system and its reflector configuration for concentrating solar radiation toward the focal region.



Figure 3: LFR system installed at Harran University Osman bey Campus, Türkiye



Figure 4: Experimental parabolic dish concentrating solar system located at the Solar Platform of Hermosillo, Mexico

In PDCs, the concentration and distribution of solar radiation across the receiver depend on several design parameters, particularly reflector shape, focal length, surface accuracy, and tracking precision. Cisneros-Cárdenas et al.[18] studied this distribution using experimental optical measurements and numerical modeling. Their results showed that the solar flux was unevenly distributed near the focal region. Receiver position and geometry therefore need careful consideration, since both influence energy absorption and the formation of localized thermal stresses. The way the different components work together is also important in PDC design. García-Ferrero et al.[19] examined the optical and thermal configurations of PDCs, including reflector geometry, receiver design, HTF selection, and power-conversion arrangements. Their review identified three major barriers to commercial implementation: the complexity of system integration, the expense of manufacturing and maintenance, and the challenges of incorporating TES. Nevertheless, the modular nature of PDCs and their ability to reach high operating temperatures make them relevant to decentralized power generation and specialized thermal applications. At elevated temperatures, receiver performance becomes a particular concern because conventional designs can lose considerable amounts of heat through convection and radiation. Cavity receivers and modified absorbing surfaces have therefore been investigated as ways of limiting these losses. Liu et al. [20] proposed a topology optimization method for a cavity receiver with interconnected internal flow channels. Experimental work has also addressed the effects of modifications to receiver geometry. Vishnu and Senthil[21] tested a PDC fitted with a finned receiver and using water as the HTF. At a mass flow rate of 0.152 kg/s, the average energy and exergy efficiencies were 67.81% and 8.93%, respectively. The economic analysis further showed that receiver modifications need to be assessed not only in

terms of thermodynamic improvements but also their economic feasibility. The heat-transfer mechanisms responsible for these improvements are discussed in Section 4.

STCs: In STCs, solar radiation is concentrated by a distributed field of heliostats, each equipped with an independent tracking mechanism that directs sunlight towards a receiver at the top of a central tower. The receiver absorbs the incoming solar flux and transfers the resulting heat to a working medium, most commonly water, molten salt, or air. Depending on the plant configuration, this thermal energy may be supplied directly to industrial processes or used to operate a power cycle for electricity generation. Compared with line-focus collectors, the tower configuration supports substantially higher concentration ratios and operating temperatures, making it particularly relevant to high-temperature power generation and integration with TES[22]. STC operation is governed by the combined effects of heliostat-field optical performance, the accuracy of mirror positioning and solar tracking, receiver thermal behavior, and fluctuations in incident solar radiation. Of particular importance is the arrangement and orientation of the heliostats, since these determine how effectively the reflected sunlight is directed toward the receiver. They also affect optical losses and the way heat flux is distributed across the receiver surface. Field layout and control strategies consequently play an important role in determining the performance of the complete system[22,23]. Figure 5 shows the heliostat field at the Yanqing CSP tower plant in China, where the mirrors are arranged to direct sunlight toward the central receiver.

Recent work on STCs has examined ways of adjusting heliostat aiming to distribute solar flux more evenly over the receiver surface and avoid localized heat-flux peaks. Experimental studies have evaluated deterministic optimization methods, while reinforcement learning has been explored for modifying aiming positions as operating conditions change[23,24]. Changes in DNI can also be classified to help coordinate heliostat-field operation with receiver control. This approach can make system operation more flexible and help limit thermal stresses[25]. Although STCs can operate at high temperatures and are well suited to thermal storage integration, their practical application is still limited by several factors. The high cost of establishing the heliostat field, heat losses from the receiver and optical system, mirror-positioning errors, and uneven heat-flux distribution remain major limitations of STCs. Overcoming these constraints requires coordinated improvements in heliostat-field layout, receiver configuration, and operational control to limit optical losses and maintain more uniform thermal loading.

PERFORMANCE ENHANCEMENT STRATEGIES FOR CSCS

Optical Design and Solar Tracking Optimization: The optical performance of a collector is largely determined by how effectively its reflector system captures and redirects incoming sunlight. This depends on several design and operational parameters, particularly reflector geometry, surface reflectivity and finish, receiver positioning, and tracking accuracy. Deviations in any of these parameters can reduce the solar energy ultimately intercepted by the receiver. Variations in any of these parameters can affect the amount of solar energy collected by the receiver. Improving optical performance requires attention to these factors together, particularly because losses arise from imperfect reflectivity, surface deviations, shading, blocking, cosine effects, tracking errors, and spillage. The contribution of each loss mechanism differs among collector technologies. The factors governing optical performance differ among collector technologies. For PTCs, optical performance is closely related to the accuracy of the parabolic reflector, its surface quality, and its alignment with the receiver. These factors affect how accurately sunlight is focused along the absorber tube. In LFRs, mirror-row spacing and orientation influence shading and blocking, and therefore the amount of radiation reaching the receiver. PDC performance depends strongly on reflector surface accuracy and alignment with the focal region. In STCs, the arrangement of the heliostat field, mirror geometry, and aiming strategy determine how solar flux is distributed across the receiver[26–28]. Collector design involves more than maximizing the amount of sunlight intercepted. Optical design choices are shaped by practical constraints, including receiver size, land requirements, structural limitations, and installation expenses. A wider receiver aperture can capture a larger fraction of the reflected radiation, reducing optical losses. However, the additional exposed surface increases the potential for heat dissipation, creating a trade-off between radiation capture and thermal performance. Increasing the reflector area or the number of mirrors can raise the amount of solar energy collected, although additional structures bring higher costs and may introduce further shading, blocking, and maintenance requirements. Optical performance must therefore be considered together with the engineering limitations and costs associated with each configuration[27]. Solar tracking

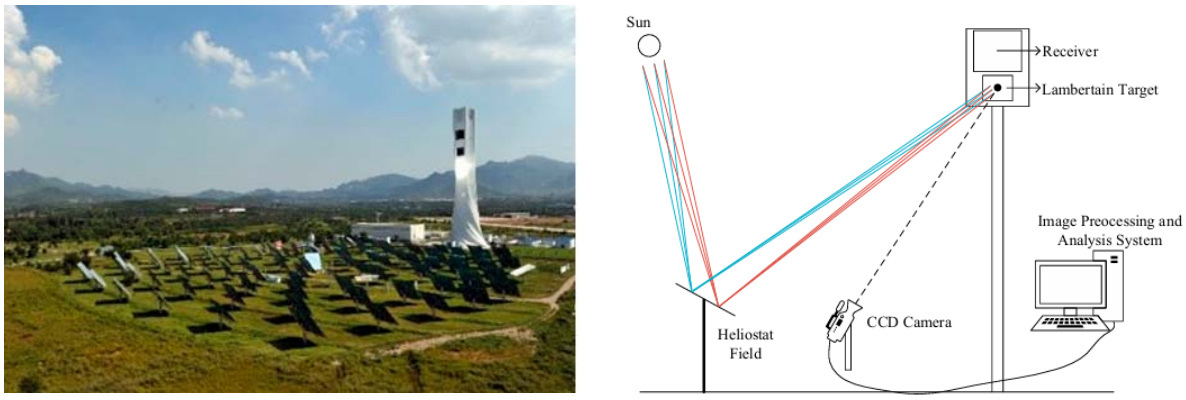


Figure 5: Perspective view of the heliostat field at the Yanqing concentrated solar power tower plant in China

helps maintain the required alignment between the collector and the Sun throughout operation. PTCs and LFRs generally operate with single-axis tracking. PDCs need to track the Sun along two axes to keep the reflected radiation focused on the receiver. In STCs, precise heliostat positioning is critical because each mirror must direct its reflected beam onto the central receiver. Small deviations in mirror orientation can shift the focal position, causing part of the reflected radiation to miss the receiver and increasing optical losses[28]. Tracking accuracy is governed by the performance of solar-position algorithms, actuator control, sensor calibration, and mechanical alignment. Two main approaches are commonly used. Open-loop systems calculate the required collector position from the geographical coordinates and the calculated position of the Sun. Closed-loop tracking systems take a feedback-based approach. Hybrid systems combine calculated positioning with feedback-based correction. The choice among these arrangements depends on the required accuracy, available budget, environmental conditions, and maintenance needs. For large heliostat fields, control becomes more demanding because the position of each mirror and its optical relationship with the receiver must also be taken into account[26,28].

Work on heliostat technology has examined changes in mirror geometry, focusing capability, tracking accuracy, and the arrangement of mirrors across the field. Some collector designs maintain better optical performance at different solar incidence angles. However, this advantage may come with added manufacturing complexity, greater structural demands, and more difficult operation. These requirements can offset part of the optical gains obtained[28]. Better coordination between optical design and tracking can increase the radiation intercepted by the receiver and improve energy delivery. Whether these improvements are worthwhile depends on the associated thermal losses and the economic conditions under which the system operates.

Receiver Design and Heat Transfer Enhancement: The amount of heat delivered by CSCs depends on more than the solar radiation reaching the receiver. The transfer of heat through the receiver wall and into the working fluid is equally important. The geometry of the receiver has a direct influence on heat transfer, since it determines the available surface area, fluid-flow pattern, boundary-layer development, and temperature distribution. One approach to improving heat transfer is to modify the absorber tube or incorporate additional devices inside it. Such modifications are particularly relevant to PTCs, where the incident solar flux is often distributed unevenly around the receiver circumference. Although these modifications help reduce temperature differences across the absorber, they can also increase hydraulic resistance and the pumping power required to circulate the HTF[29]. Other enhancement methods leave the overall receiver design unchanged and focus instead on its inner surface. Corrugations, grooves, and dimples are used for this purpose. These features disturb the thermal boundary layer and promote fluid mixing, without substantially affecting the external optical configuration. Other passive enhancement devices include twisted tapes, wire coils, fins, rings, and porous structures. Their contribution to convective heat transfer is associated with the formation of swirling motion, secondary flows, and localized flow separation. Their performance varies with the geometry and dimensions of the inserts, their spacing, the flow regime, and operating conditions. Greater obstruction of the flow passage, however, can cause a substantial rise in pressure drop[29]. Changes to the receiver cross-section have also been investigated as a way of enhancing heat transfer. In one experimental

study, a receiver incorporating a finned rectangular channel achieved a higher convective heat-transfer coefficient than a conventional design. Changes to the flow-channel design and a larger heat-transfer surface can improve the rate of heat exchange. However, the heat-transfer coefficient alone is not enough to judge the overall performance of the receiver. Flow rate, supplied heat, operating temperature, and pumping power also need to be considered when comparing the two configurations[30]. More complex internal receiver arrangements have been studied to reduce temperature gradients and obtain a more uniform temperature distribution. One numerical investigation considered a parabolic trough receiver fitted with an optimized conical-strip insert under nonuniform thermal loading. The insert was intended to increase radial mixing and disturb the flow close to the receiver wall, thereby reducing localized regions of high temperature. The benefit depends on the particular arrangement used, since additional friction and pumping requirements can offset improvements in heat transfer[31]. Receiver enhancement methods need to be compared using both thermal and hydraulic measures. Relevant indicators include the Nusselt number, friction factor, pressure drop, heat-transfer rate, and thermal efficiency. Where appropriate, the performance evaluation criterion (PEC) provides a way to examine whether the improvement in heat transfer is sufficient to compensate for the additional flow resistance. A review of passive heat-transfer enhancement techniques for PTC absorber tubes reported considerable variation in both thermal improvement and friction-related losses across the geometries examined. This variation makes consistent evaluation criteria particularly important when comparing results obtained under different operating conditions[32]. Receiver design also has an important bearing on the thermal performance of point-focus collectors, including parabolic dish systems and STCs. Several design features influence heat absorption and thermal losses, among them cavity geometry, aperture dimensions, the arrangement of internal flow channels, and the distribution of incident solar flux. These factors need to be considered together when designing a receiver. In particular, improvements in heat transfer should not come at the expense of temperature uniformity, structural strength, or acceptable hydraulic performance. These considerations are important when seeking higher useful thermal output without introducing excessive pressure losses, local overheating, difficult manufacturing processes, or additional maintenance demands.

Nanofluids and Advanced HTFs: The HTF used in a CSC determines, to a considerable extent, its thermal performance and operating temperature range. Common choices include synthetic thermal oils, water/steam, and molten salts. The selection depends on the temperature required by the process, the fluid's thermophysical properties, its compatibility with system materials, and the requirements of the energy conversion equipment operating downstream. Since conventional fluids have limitations in heat-transfer performance, nanofluids and other advanced working fluids have attracted research interest. Their suitability for practical use, however, also depends on hydraulic behavior, stability, reliability, and cost[33]. Nanofluids are prepared by dispersing nanoscale particles in a base fluid. In PTC applications, nanofluids have been formulated using different particle types, including metal oxides (e.g., Al O and CuO), metallic nanoparticles, and carbon-based materials. Their thermal behavior varies with the characteristics of the dispersed particles and their concentration in the base fluid, affecting both thermal conductivity and convective heat transfer. Experimental and numerical investigations have consequently examined the roles of particle size and composition, loading concentration, base-fluid properties, and mass flow rate in determining collector performance. These parameters have been considered in relation to heat transfer, outlet temperature, and energy and exergy efficiencies. The extent of improvement, however, depends on the fluid formulation and operating conditions, so results obtained for one collector configuration cannot necessarily be applied to others [34]. Despite their potential, nanofluids can present practical problems during operation. Although adding more nanoparticles can increase the thermal conductivity of a base fluid, the resulting suspension does not necessarily perform better overall. Higher particle loading can make the fluid more viscous, intensify flow resistance, and increase pressure drop, placing a greater demand on the pumping system. Stability is another concern during prolonged operation: suspended particles may gradually cluster or settle, altering the fluid's properties and compromising its performance over time. Dispersants, suitable preparation methods, and ultrasonication have been used to reduce these problems. However, their effectiveness under realistic operating temperatures and extended fluid circulation remains to be established. Thermal conductivity alone is not enough to assess the performance of these fluids. A meaningful assessment of nanofluids should extend beyond their thermophysical properties to include the actual heat delivered by the collector, outlet temperature, thermal efficiency, and the energy consumed by fluid circulation. Whether the reported gains persist over time remains an open question, requiring further experimental validation and stability testing under sustained operating conditions [35].

Hybrid nanofluids contain more than one type of nanoparticle, allowing the thermophysical properties of the base fluid to be modified through different particle combinations. Their behavior depends on particle composition, mixing ratio, concentration, dispersion stability, and viscosity. Some formulations provide better heat transfer, but the additional preparation costs and difficulties in maintaining stable suspensions make comparison with conventional base fluids necessary under equivalent thermal–hydraulic conditions. Molten salts remain another important option for high-temperature CSP systems, especially where heat transport and TES are used together. Their application is limited by freezing risks, corrosion, compatibility with system materials, and allowable operating temperatures. The choice of fluid should therefore be based on the useful thermal output and performance of the complete system, rather than on improvements in individual thermophysical properties alone[36].

Further experimental work is needed to establish how advanced HTFs perform over extended operating periods. Comparisons should use consistent thermal–hydraulic conditions, supported by reliable measurements of fluid properties over the relevant temperature ranges. Economic assessments also need to account for fluid preparation, pumping energy, maintenance, material compatibility, and the feasibility of producing these fluids at an industrial scale. Such evidence is necessary to determine whether advanced HTFs can offer lasting performance improvements at costs suitable for commercial concentrating solar systems.

Operating Parameters and Thermal Performance Optimization: Solar irradiation, weather conditions, fluid properties, and operating settings all influence the thermal output of CSCs. Even when the collector geometry is kept unchanged, variations in DNI, ambient temperature, wind speed, inlet-fluid temperature, or mass flow rate can lead to changes in useful heat gain and thermal efficiency. The extent of these changes is also related to receiver design and the heat losses occurring during operation. Optimizing one parameter in isolation may therefore overlook its influence on other aspects of collector performance[37,38]. Mass flow rate and inlet temperature affect convective heat transfer and the temperature rise of the working fluid. A higher mass flow rate generally leads to a smaller temperature difference between the receiver inlet and outlet. At the same time, greater heat removal from the receiver can lead to an increase in useful thermal output. This improvement does not continue indefinitely, however. At sufficiently high flow rates, the additional thermal gain becomes relatively small, whereas pressure drop and pumping power continue to increase. Reducing the flow rate may result in a higher outlet temperature, but this does not necessarily mean that more useful heat is delivered. The appropriate operating conditions depend on whether the system is intended to deliver heat at a specified temperature, maximize thermal output, or reduce auxiliary energy consumption[37,38]. Thermal efficiency and exergy efficiency represent different aspects of collector performance. The former relates useful heat output to the incident solar energy, while the latter takes account of energy quality and thermodynamic irreversibilities. A multi-objective PTC design study considered both measures during optimization. The results showed that maximizing heat collection does not necessarily lead to the best thermodynamic performance. This is particularly evident when the temperature of the delivered heat falls short of application requirements or when considerable thermodynamic irreversibilities are present[39].

The economic viability of PTC designs also depends on the cost of delivered heat. A techno-economic study used a multi-objective genetic algorithm to identify configurations that balance higher thermal efficiency with a lower levelized cost of heat. The study optimized these design variables as a combined set, rather than treating them independently, covering HTF selection, absorber materials, selective coatings, and collector geometry. The analysis showed that improvements in thermal efficiency and reductions in heat production costs were achievable, although the most favorable design varied according to the target heat-delivery temperature and the economic assumptions underlying the assessment[40]. Collector output is also sensitive to fluctuations in weather and incident solar radiation. The available DNI sets the amount of direct solar energy reaching the collector, while ambient temperature and wind influence heat dissipation from the receiver. Moreover, an uneven distribution of solar flux can create localized overheating, producing temperature gradients across the receiver surface. Such conditions may subject the material to repeated thermal stresses and eventually affect component durability. A comparative review of PTC, LFR, PDC, and STC technologies discussed the importance of coordinating the incident solar flux distribution with the heat-transfer capacity of both the receiver and the working fluid. Accordingly, collector optimization needs to consider local temperature variations rather than depending exclusively on average irradiance and outlet temperature[41]. The balance between collector performance and cost also varies across technologies. In LFR systems, mirror layout and

geometric parameters affect optical efficiency, annual energy production, and the cost of the solar field. A bi-objective optimization study compared annual energy performance with specific direct solar-field costs. The results indicated that nonuniform geometric arrangements may provide economically favorable designs without causing a substantial reduction in energy performance[42]. Control strategies offer another means of improving system operation when solar conditions vary. An exergy-based hierarchical control approach considered operating constraints, start-up and shut-down behavior, and pump operation. The study found that control aimed only at maximizing energy output or temperature may perform less effectively than an approach based on exergy[43]. The choice of operating strategy consequently depends on the intended application and the relative importance of useful heat gain, thermal and exergy efficiencies, pumping power, heat losses, and levelized heat costs. Multi-objective optimization can be used to examine Pareto-optimal trade-offs among these competing requirements. Control strategies must also remain effective under the environmental variations encountered during actual operation. System performance cannot be assessed by looking at individual components in isolation. Operating conditions, receiver design, control strategies, and techno-economic factors all need to be considered, since changes in any of these can influence how the rest of the system performs.

TES INTEGRATION IN CSCS

SHS Systems: SHS is widely used in CSP plants as a TES method in which heat is stored by raising the temperature of a solid or liquid medium without changing its phase. The amount of heat retained in the storage medium depends on three main factors: the mass of the material, its specific heat capacity, and the temperature interval over which it operates. Stored heat can be used to keep the plant running when solar irradiation drops. Stored heat can be drawn upon during periods of inadequate solar irradiation, allowing the power plant to maintain electricity generation even when direct solar input declines or becomes unavailable. This capability also provides greater flexibility in matching power output to demand[44]. One commonly used arrangement is the two-tank molten-salt system. During charging, heated salt is pumped into an insulated hot tank. When heat is needed, the hot salt passes through a steam-generation unit and, after releasing its energy, returns to a separate cold tank. Although this configuration allows heat supply to be regulated, it requires insulated storage tanks, pumping equipment, and a considerable inventory of molten salt, all of which contribute to investment and operating expenses[45]. Storage-medium selection depends on the required operating temperature, thermophysical properties, chemical stability, material compatibility, and cost. Water is commonly used for low-temperature storage, whereas thermal oils are suited to intermediate-temperature applications. Molten salts, in turn, are commonly selected for high-temperature CSP applications. Molten salts, however, present difficulties associated with freezing, corrosion, and thermal stability. Their properties must therefore be carefully matched to the conditions under which the system operates[46]. Packed-bed storage provides another option, in which a HTF flows through a bed of solid materials, such as rocks or ceramic particles, allowing heat to be stored and later recovered. Performance depends on particle properties and size, bed porosity, flow distribution, and fluid–solid heat transfer. While inexpensive filler materials may reduce storage costs, pressure drop, pumping demand, and flow nonuniformity remain important design constraints[47]. Thermocline systems use a single tank with hot and cold regions separated by a temperature-gradient zone, potentially reducing tank costs and, when solid fillers are incorporated, expensive fluid inventory. Mixing, heat losses and uneven fluid flow can disturb thermal stratification in the storage medium, reducing the amount of energy that can be recovered for practical use. The choice among two-tank, packed-bed, and thermocline systems therefore depends on the required operating temperature, storage period, heat-transfer characteristics, and project economics. SHS can serve as a practical storage option in CSP plants, provided that the storage material and system configuration are suited to the requirements of the solar field and power block[48].

LHS and PCMs: LHS stores thermal energy through material phase transitions, primarily solid–liquid changes. Unlike SHS, which relies on temperature variations, LHS absorbs and releases substantial energy within a narrow temperature range, making PCMs attractive for compact thermal storage and temperature regulation in concentrating solar systems[49]. As shown in Figure 6, sensible heat is stored or released during temperature changes, whereas latent heat is exchanged during phase transitions at approximately constant temperature[50].

PCMs used in solar thermal applications fall into three material families, each with distinct thermal characteristics. Paraffins and fatty acids are widely studied among organic PCMs because they remain

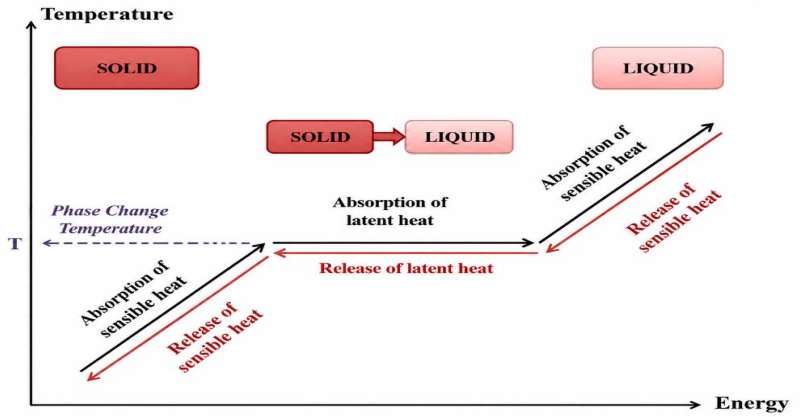


Figure 6: Sensible and latent heat storage characteristics

chemically stable and are relatively non-corrosive. Their low thermal conductivity, however, slows heat exchange. Inorganic materials, particularly salt hydrates and high-temperature salts, provide substantial heat-storage capacity and are therefore considered for applications operating at medium and high temperatures. Eutectic compositions offer a different approach: by adjusting the proportions of their constituents, their phase-change temperatures can be matched to the thermal requirements of a particular system[51]. Selecting a PCM for CSP applications requires balancing several material properties, particularly melting temperature, thermal conductivity, stability under repeated heating and cooling, and compatibility with HTFs and containment materials. One approach to improving heat transfer during storage and recovery is cascaded LHS, in which several PCMs with different melting points are arranged within the storage unit. Michels and Pitz-Paal[52] investigated this concept in parabolic trough power plants, examining how the choice of phase-change temperatures affects heat-transfer behavior. Other experimental investigations have also explored the incorporation of PCMs into CSC systems. Guerraiche et al. [53] investigated a PTC fitted with a PCM-based receiver and reported better thermal performance than that of a conventional configuration. Bagherzadeh et al.[54] studied a cascaded LHS unit integrated with a PTC, examining how the PCMs melted and how this process affected the thermal and exergy performance of the system. A persistent difficulty with PCM-based storage is the slow heat exchange caused by the materials' low thermal conductivity. This limits the speed at which the PCM can melt and solidify, restricting both the rate of energy storage and its subsequent recovery. Material-related problems further complicate operation, including supercooling, phase segregation, expansion or contraction during phase transitions, incompatibility with containment materials, and deterioration after repeated thermal cycles. The choice of PCM and containment material, together with measures to improve heat transfer and appropriate phase-change temperatures, must therefore be considered in the design of a reliable storage system.

Advanced Thermal Storage Configurations: Researchers have also explored TES arrangements that differ from conventional storage systems, either by combining storage materials or changing the system configuration. The aim is to increase the amount of heat that can be stored, improve its delivery, allow more flexible operation, and keep costs under control. Approaches under investigation include packed beds, encapsulated PCMs, and systems that bring together different heat-storage mechanisms. Their performance varies with operating temperature, heat-transfer characteristics, control strategies, and the way storage is integrated into the CSP plant. In single-tank thermocline systems, hot and cold regions are separated by a zone across which temperature changes gradually. Replacing part of the heat-transfer fluid with inexpensive solid fillers can reduce the required fluid inventory and, consequently, the overall storage cost. Encapsulated PCMs placed at selected positions within the tank may also increase the available storage capacity or help maintain more stable temperatures during discharge. Uneven flow distribution, heat losses, and movement of the thermocline can nevertheless disturb temperature stability. These effects need to be assessed in relation to power-block requirements and the performance of conventional two-tank systems[55]. Hybrid sensible–latent storage combines temperature-dependent sensible heat capacity with the latent heat of PCMs. In packed-bed configurations, sensible storage media provide the primary storage volume, while PCM layers can enhance

energy density and prolong useful discharge temperatures. A numerical study reported an increase in storage capacity, together with longer effective charging and discharging periods under the operating conditions examined. The extent of these improvements varied with PCM volume fraction, melting temperature, layer arrangement, and encapsulation costs. The results may therefore not apply equally to other storage configurations[56]. Encapsulating PCM makes it possible to incorporate the material into packed beds without direct contact with the circulating heat-transfer fluid. The shape of the capsules and the material used for their walls affect heat-transfer area, thermal resistance, mechanical strength, and the volume of PCM available for storage. The capsules must also accommodate expansion and contraction as the material changes phase. Their design consequently needs to account for storage-bed geometry and operating conditions as well as PCM thermal properties, rather than considering latent heat capacity alone[56]. Some advanced thermal storage concepts combine latent and thermochemical storage, using PCM phase transitions alongside reversible chemical reactions or sorption processes. Tescari et al.[57] carried out an experimental investigation of a pilot-scale redox-based thermochemical storage unit at a solar tower facility. Their system used cobalt oxide coated onto cordierite honeycomb structures and was subjected to 22 charge–discharge cycles. The results showed that thermochemical storage could operate under conditions approaching those of a solar power plant, while also drawing attention to reaction behavior and the management of heat during repeated cycles. For CSP applications, Mellouli et al.[58] proposed a hybrid cascaded storage arrangement in which dual metal-hydride beds are combined with cascaded PCMs. Their numerical model, validated against experimental data and mass and energy balances, predicted an approximately 19% reduction in charging and discharging cycle duration under the investigated conditions. Although such configurations can integrate complementary storage mechanisms, they introduce greater design complexity, material compatibility constraints, and control requirements than conventional sensible or latent storage systems[58].

Advanced TES configurations differ in the benefits they provide and the limitations they introduce. Thermocline and packed-bed configurations provide alternatives for simplifying storage system design while reducing associated costs. Hybrid sensible–latent systems, by comparison, seek to store more energy and maintain a steadier temperature during discharge. Thermochemical–latent configurations take a different approach, combining two storage mechanisms that can complement one another. The choice between these designs depends on how long heat must be stored, the operating temperature, the required heat-delivery conditions, system complexity, and project economics. Storage capacity alone is not sufficient for comparing these configurations. The assessment should also establish how much of the stored energy can actually be recovered, how well the discharge temperature is maintained, the extent of thermal losses, how the system performs over repeated cycles, and what auxiliary equipment is needed.

Effects of Thermal Storage Integration on System Performance: Integrating TES into CSCs allows heat to be supplied even when solar energy is unavailable, although the storage system also introduces additional thermal losses and auxiliary energy consumption. Its effectiveness depends on storage capacity, energy recovery, and discharge temperature. Performance evaluation must therefore distinguish collector efficiency, storage charging and discharging efficiencies, and overall integrated system efficiency[59]. TES can stabilize useful heat delivery during fluctuating solar irradiation. Kumaresan et al.[60] experimentally examined a PTC system connected to a sensible-heat storage tank. The assessment covered four aspects of system operation: useful heat delivered, charging efficiency, energy retained in storage, and performance over a complete day. Importantly, the collector and storage tank were treated as a coupled system, since their interaction determines how much of the collected energy reaches the application. While the storage unit is being charged, some of the heat produced by the collector is withheld from immediate use and retained for later demand. It can then be recovered when solar irradiation weakens, helping maintain the required thermal supply. The energy ultimately available, however, is lower than the amount initially stored because heat escapes through the tank walls, connecting pipework, and heat exchangers. In CSP plants, TES can extend operating hours, reduce shutdown–restart cycles, and shift electricity generation toward periods of higher demand. However, improvements in power-cycle efficiency do not necessarily translate into proportional annual performance gains. An annual simulation of high-temperature central-receiver plants reported an increase of less than 2% in average annual solar-to-electric efficiency despite an improvement exceeding 8% in thermal-to-electric conversion efficiency.

Increased thermal losses and startup–shutdown losses contributed to this discrepancy[61]. TES performance should also be evaluated through energy and exergy analyses. Energy analysis is concerned with the quantity of heat or electricity delivered by a system, whereas exergy analysis also takes into account the quality of that energy and the irreversibilities occurring during its conversion and transfer. Not all of the energy stored in a TES system can be recovered for useful purposes. Energy losses arise from irreversible processes, including heat transfer across finite temperature differences, fluid mixing, and power conversion. Consequently, a large storage capacity alone does not guarantee effective system operation. If the discharge temperature falls below the requirements of electricity generation or industrial applications, the recovered heat may have considerably reduced practical value. Maintaining a suitable discharge temperature and preventing excessive thermal degradation are therefore important aspects of storage operation.

Auxiliary electricity consumption by pumps, fans, controls, and heat-transfer equipment further affects net performance. An analysis of a Joule–Brayton pumped TES system integrated with a CSP plant reported an exergy round-trip efficiency of approximately 54%, compared with 60% for the standalone storage system[62]. The comparison shows that sharing components and integrating different parts of a system do not always lead to improvements across every performance indicator. The way different subsystems interact, together with the strategies adopted to operate them, can also influence overall system performance.

COMPARATIVE PERFORMANCE ASSESSMENT OF CSCS

Optical and Thermal Performance Comparison: Optical and thermal efficiency are closely related, although they describe two different aspects of CSC performance. Optical efficiency quantifies the fraction of incident solar radiation that reaches and is absorbed by the receiver. The latter measures the useful heat obtained from the collector in relation to the incident solar energy, with the effect of thermal losses taken into account. Both measures vary with collector geometry, tracking accuracy, optical properties, receiver design, operating temperature, flow rate, and ambient conditions. Reliable comparisons therefore require consideration of measurement conditions alongside reported efficiencies [63,64]. Kincaid et al.[63] used annual ray-tracing simulations at China Lake, California, to compare linear Fresnel, parabolic trough, and central receiver systems. The calculated annual optical efficiencies were 60% for parabolic trough, 52% for central receiver, and 40% for linear Fresnel systems. The lower efficiency of the Fresnel configuration was mainly associated with shading, blocking, and reduced optical interception. Liu et al.[64] combined SolTrace and CFD simulations to investigate the effect of operating conditions on an LS-2 PTC. Their model predicted an optical efficiency of 74.5%, close to the experimental value of 73.7%. Under a modeled cold-climate condition, the instantaneous thermal efficiency reached 63.87%. The analysis further showed that collector performance was strongly influenced by inlet-fluid temperature and solar irradiance. Santos-González et al.[65] developed a numerical model for a CPC with a geometric concentration ratio of 1.8 and an acceptance angle of 30°. The model predictions differed from the experimental thermal-efficiency measurements by an average of ±6.4%. Abd et al.[66] experimentally assessed an outdoor CPC fitted with a flat-plate receiver in Mosul, Iraq. The collector, operating at a concentration ratio of 1.5, achieved a maximum efficiency of 26.5%. Although increasing the water mass flow rate enhanced efficiency, it resulted in a lower outlet temperature, illustrating the trade-off between heat extraction rate and the temperature of the delivered fluid. Chafie et al.[67] assessed a parabolic trough receiver under contrasting meteorological conditions, comparing its energy and exergy performance. The measurements revealed higher efficiencies during clear-sky operation than under cloudy conditions, demonstrating the sensitivity of both performance indicators to changes in direct solar irradiance and atmospheric conditions. Chen et al.[68] theoretically and experimentally compared a CPC-integrated evacuated-tube absorber with a conventional all-glass evacuated tube. Under the tested conditions, the thermal efficiencies reached 68.9% and 54.3%, respectively. These results indicate that optical concentration improved the thermal performance of the absorber in the configuration investigated. In a separate experimental study, Mawire and Taole[69] evaluated an SK-14 parabolic dish receiver. Under high solar irradiation, they reported an optical efficiency of approximately 52%, together with an average heat-loss coefficient of 4.6 W/K. The exergy efficiency was considerably lower than the energy efficiency, indicating that the amount of collected heat alone does not fully represent its potential to produce useful work.

Arunachala[70] experimentally evaluated twisted-tape inserts in a parabolic trough receiver under beam irradiance of 400–750 W/m². Maximum instantaneous efficiencies increased from 19.1% for the

plain receiver to 22.3%, 29.5%, and 40% at twist ratios of 5.2, 4.1, and 2.7, respectively. The corresponding effective thermohydraulic efficiencies were 21.8%, 29.3%, and 39.7%. These results indicate that passive heat-transfer enhancement can improve performance, although the associated hydraulic penalties must also be considered. Karathanassis et al.[71] developed and experimentally tested a parabolic-trough concentrating photovoltaic thermal (CPVT) system. The system reached an overall efficiency of approximately 50%, comprising 44% thermal and 6% electrical efficiency. The quality of the optical components was identified as one of the main factors restricting its performance.

Palacios et al.[72] examined different receiver configurations incorporating Fresnel lenses through a combination of numerical simulations and experimental testing. In the simulations, the highest temperature (116°C) was obtained with a Fresnel lens and a black receiver pipe, at an irradiance of 1,000 W/m². The corresponding experimental temperature was 96°C at 983 W/m². The difference between these results shows why numerical predictions need to be checked against experimental measurements under realistic operating conditions. Guerraiche et al.[73] studied a PTC with a PCM incorporated into its receiver, using both experiments and numerical analysis. Compared with the conventional design, the modified receiver increased the maximum outlet-water temperature by 14.86–16.80% and daily thermal efficiency by 6.56–8.32%. Useful heat delivery was sustained for approximately 1.7–2 h. This suggests that incorporating PCM into the receiver can help maintain thermal output when solar availability temporarily decreases.

Bagherzadeh et al.[74] experimentally examined cascaded LHS in a PTC. Combining PCMs with different melting temperatures improved melting behavior and increased stored energy by more than 22% compared with a non-cascaded arrangement. Higher heat-transfer-fluid flow rates also improved collector efficiency and shortened PCM melting time. Farhan et al.[75] experimentally evaluated a non-tracking CPC using silica-based and hybrid nanofluids containing MgO–carbon black or carbon black–graphene nanoplatelets. With a nanoparticle concentration of 0.015 wt% and a mass flow rate of 0.010 kg/s, the MgO–carbon black nanofluid reached a thermal efficiency of approximately 38.51%. The outlet temperature increased by 8.5°C compared with the reference condition. These results indicate its potential for improving heat transfer in non-tracking concentrators.

Khaledi et al.[76] investigated the performance of a CPC using a hybrid nanofluid prepared with an ethylene glycol–water base fluid and containing SiO and multiwalled carbon nanotubes. Their assessment covered energy, hydraulic, and exergy performance. The nanofluid-based configuration delivered higher thermal and exergy efficiencies than the base fluid, with improvements reaching 14.27% and approximately 45%, respectively. This enhanced performance was accompanied by a rise in pumping power of up to 9.72%. The additional energy consumed in maintaining fluid circulation therefore needs to be included when determining whether the thermal gains translate into an overall improvement in system performance.

Ajay and Kundan[77] evaluated three working fluids—water, CuO–water, and SiO –water—in a parabolic solar collector. Their investigation combined experimental testing with CFD analysis to examine how nanoparticle addition affects collector thermal performance. The nanoparticle concentration was maintained at 0.01 vol%. At flow rates of 40 and 80 L/h, the efficiency improvement ranged from 6.68% to 7.15% for SiO –water and from 7.64% to 8.42% for CuO–water. Elahi et al.[78] tested a hybrid solar water-heating system incorporating an evacuated-tube collector, a parabolic concentrator, paraffin PCM, and nanofluids containing either Al O or ZnO. At a nanoparticle concentration of 0.2 wt%, ZnO increased the maximum reservoir temperature by 10.74%, compared with 7.25% for Al O . The corresponding improvements in average thermal efficiency were 41.6% and 33.9%, respectively.

CSC performance depends on the interplay between collector geometry, receiver configuration, operating conditions, and heat-transfer characteristics. PTCs and central receiver systems have shown favorable optical performance in some large-scale applications, whereas CPCs remain relevant to processes requiring low- to medium-temperature heat. Receiver modifications, PCM integration, and nanofluids can improve specific performance indicators, although their effectiveness remains configuration- and condition-dependent. Table 2 summarizes the reported optical and thermal performance of the reviewed systems.

Technical and Operational Trade-offs: The practical suitability of CSCs depends on technical and operational trade-offs beyond optical and thermal efficiency, including capital costs, receiver heat losses, tracking accuracy, pumping requirements, water consumption, and thermal storage configuration. Higher efficiency does

Table 2. Comparative optical and thermal performance of CSCs

Ref.	Collector / configuration	Method	Main reported result
[63]	Linear Fresnel, parabolic trough, central receiver	Annual ray-tracing simulation	Optical efficiency: 40%, 60%, and 52%, respectively
[64]	Parabolic trough (LS-2)	Numerical / reference experiment	Optical efficiency: 74.5%; experimental reference: 73.7%
[65]	CPC	Numerical and experimental	Mean deviation in thermal-efficiency prediction: ±6.4%
[66]	CPC with flat-plate receiver	Experimental	Maximum efficiency: 26.5%
[67]	Parabolic trough receiver	Experimental energy and exergy analysis	Higher average performance under clear-sky than cloudy conditions
[68]	CPC absorber vs. evacuated tube	Experimental and theoretical	Thermal efficiency: 68.9% vs. 54.3%
[69]	Parabolic dish receiver	Experimental	Optical efficiency: approximately 52%; heat-loss coefficient: 4.6 W/K
[70]	Parabolic trough with twisted-tape inserts	Experimental	Maximum instantaneous efficiency: 40%, compared with 19.1% for a plain receiver
[71]	CPVT	Experimental	Overall efficiency: approximately 50% (44% thermal + 6% electrical)
[72]	Concentrator with Fresnel lens	Numerical and experimental	Receiver temperature: 116°C simulated and 96°C experimentally
[73]	Parabolic trough with PCM	Experimental and numerical	Daily thermal-efficiency improvement: 6.56–8.32%
[74]	Parabolic trough with cascaded PCM	Experimental	Reported stored-energy increase: more than 22%
[75]	CPC with hybrid nanofluid	Experimental	Thermal efficiency: approximately 38.51% under the reported conditions
[76]	CPC with hybrid nanofluid	Experimental energy, hydraulic, and exergy analysis	Thermal-efficiency improvement: 14.27%; pumping-power increase: up to 9.72%
[77]	Parabolic collector with CuO–water and SiO2–water nanofluids	Experimental and CFD	Reported efficiency improvements: 6.68–8.42%, depending on nanofluid and flow rate
[78]	Hybrid solar collector with PCM and nanofluid	Experimental	Average thermal-efficiency improvement: 33.9–41.6%, depending on nanofluid

not necessarily ensure superior economic or operational performance. PTCs tend to provide better optical efficiency than LFRs. However, LFRs have a simpler structural design, which may make them less expensive to construct. The use of nanofluids and modified receivers presents a similar compromise: better heat transfer may be accompanied by higher hydraulic resistance and increased auxiliary power consumption. Morin et al.[79] investigated this trade-off in a 50 MW solar thermal power plant based on direct steam generation. Their analysis determined the break-even solar-field investment cost required for LFRs to compete economically with PTC-based systems. Cocco and Cau[80] evaluated 1 MWe solar power plants integrating PTCs or LFRs with an ORC and two-tank thermal storage. In terms of annual electricity generation per unit of land area, LFRs achieved 50–60 kWh/(m²·year), compared with 45–55 kWh/(m²·year) for PTCs. The comparison changed when collector area was considered: PTCs delivered more energy per unit of collector area and achieved higher conversion efficiency. Electricity generation costs were estimated at approximately €380/MWh for LFRs and €340/MWh for PTCs. Thus, the greater land-use performance of LFRs did not necessarily result in higher conversion efficiency or lower electricity costs. Shokrnia et al.[81] compared PTC and LFR configurations with evacuated and non-evacuated receivers at four locations characterized by different DNI levels. Among the configurations examined, evacuated PTCs achieved the lowest LCOE. Their higher annual energy production was sufficient to offset the additional initial investment. A different pattern emerged for non-evacuated receivers, where LFRs achieved slightly lower LCOE values than comparable PTCs at several locations. These results show that the economic comparison between the two technologies depends on more than collector type alone; receiver insulation, annual energy production, and initial investment also play important roles.

Lei et al.[82] experimentally characterized parabolic trough receiver losses, including overall heat loss, end loss, and selective-coating thermal emittance. Heat losses were approximately 270 W/m when the absorber temperature reached 400°C. At lower temperatures, end losses accounted for a larger proportion of the total. These results point to the importance of receiver insulation, coating properties, and end design in determining both thermal performance and cost.

Liqreina and Qoaider[83] assessed dry versus wet cooling in a parabolic-trough CSP plant in Ma'an, Jordan. Dry cooling can considerably reduce water consumption,

particularly in arid regions. At elevated ambient temperatures, however, dry cooling can reduce power-cycle efficiency. Maintaining the same electrical output may require installing additional collector capacity, which would increase the initial investment. Consequently, the reduction in water consumption needs to be evaluated against both the potential loss of generating performance and the cost of expanding the solar field.

Malan and Kumar[84] investigated the optical sensitivity of large-aperture PTCs to reflector slope errors, tracking inaccuracies, receiver misalignment, and geometric variations. Their analysis revealed a marked deterioration in optical concentration as reflector accuracy declined: increasing the slope error from 0 to 8 mrad lowered the peak local concentration ratio from 62 to 47. Tracking errors of up to 8 mrad also led to an approximately 22% decrease in the intercept factor. These results demonstrate that a higher geometric concentration ratio does not, by itself, guarantee better optical performance. Maintaining the desired concentration performance requires high reflector surface quality, accurate receiver alignment, and precise solar tracking.

Zhang et al.[85] combined ray-tracing simulations with focal-plane heat-flux measurements to evaluate tracking and receiver-installation errors in a PTC equipped with a heat-pipe evacuated tube. Mechanical inaccuracies in the collector assembly can alter the distribution of concentrated solar radiation, even when the reflectors themselves have high optical reflectivity. Receiver misalignment and tracking deviations may cause part of the reflected energy to fall outside the intended target. In central-receiver CSP plants, Les et al.[86] assessed the consequences of heliostat-field optical errors for electricity generation and the levelized cost of energy. Their findings showed that these inaccuracies affect both energy yield and overall project economics. Tighter optical tolerances can help limit such losses, although achieving the required precision may increase manufacturing, installation, and quality-control expenses. Bhor and Bhangale[87] experimentally investigated the thermal–hydraulic performance of a PTC operating with water-based Fe O nanofluids and twisted-tape inserts under simulated solar flux. The reported PEC values ranged from approximately 1 to 2.3, with the highest performance obtained at a nanoparticle concentration of 6 vol% and a twist ratio of 2.8 for selected Reynolds numbers. The improved fluid mixing increased heat transfer, but it also raised flow resistance. The effects of these receiver modifications on overall system performance should therefore be considered alongside the associated pressure drop and pumping power requirements. Cascetta et al.[55] compared conventional two-tank TES with single-tank packed-bed configurations incorporating encapsulated PCMs in a CSP plant equipped with a linear Fresnel solar field. The single-tank configurations reduced investment costs by approximately 45% and the levelized cost of storage by 48%. Although these configurations reduced storage costs, mean ORC efficiency fell from 19.7% to 18.2%, mainly because the inlet temperature became less stable. The results indicate that reducing the cost of thermal storage does not necessarily improve the performance of the power cycle.

The findings across these studies point to several competing considerations in collector design and operation. PTCs generally offer better optical efficiency, whereas the simpler construction and more compact land requirements of LFRs may make them preferable in certain installations. Thermal management remains important for both technologies, with receiver insulation and accurate optical alignment helping to limit energy losses. Dry cooling reduces water demand but can impose an efficiency penalty on the power cycle, particularly in hot climates. Similarly, nanofluids and modified receiver geometries can improve heat transfer, although the associated increase in flow resistance may offset part of the benefit. Single-tank TES offers a less costly alternative to conventional storage arrangements, but maintaining a sufficiently stable discharge temperature remains unresolved. Therefore, technology selection should account for operating temperature, local climate, water availability, maintenance requirements, storage configuration, and lifetime energy costs rather than peak efficiency or initial investment alone. Table 3 summarizes the principal technical and operational trade-offs of CSCs.

Suitability for Different Solar Thermal Applications: The suitability of CSCs depends on operating temperature, thermal load profile, available direct solar irradiance, and required operational flexibility. The operating temperature largely determines which concentrating technology is suitable for a given application. CPCs and PTCs are commonly employed for water heating, industrial preheating, and absorption cooling, where low- to medium-temperature heat is sufficient. Applications such as utility-scale electricity generation and solar thermochemical hydrogen production impose more demanding thermal requirements, necessitating higher concentration ratios and receivers capable of withstanding elevated temperatures. The selection of a collector should therefore be based on the thermal and operating requirements of the intended application,

Table 3. Technical and operational trade-offs of CSCs

Ref.	Collector / system	Technical or operational factor	Main finding	Principal trade-off
[79]	Parabolic trough vs. linear Fresnel	Optical performance and capital cost	PTC offers higher optical efficiency; LFR has a simpler structural arrangement	Higher optical performance vs. potentially lower investment cost
[80]	PTC vs. LFR with ORC and TES	Land utilization and electricity cost	LFR offers advantages in land-related energy yield, while PTC provides higher conversion performance in the evaluated configurations	Land use vs. energy conversion efficiency
[81]	PTC and LFR with evacuated/non-evacuated receivers	Receiver heat loss and investment	Evacuated PTC achieved the lowest LCOE in the studied configurations	Lower heat loss vs. higher receiver cost
[82]	Parabolic trough receiver	Thermal losses	Receiver heat loss reached approximately 270 W/m at an absorber temperature of 400°C	High operating temperature vs. heat-loss control
[83]	CSP plant with dry or wet cooling -cycle	Water consumption and power performance	Dry cooling reduces water demand but may reduce performance during hot weather	Water conservation vs. power output
[84]	Large-aperture PTC	Optical and tracking errors	Increasing slope error from 0 to 8 mrad reduced peak local concentration from 62 to 47	Manufacturing precision vs. fabrication cost
[85]	PTC with heat-pipe evacuated tube	Tracking and installation accuracy	Tracking and receiver-positioning errors reduce intercepted solar energy	Accurate alignment vs. installation and maintenance complexity
[86]	Central-receiver CSP	Heliostat-field optical errors	Optical errors reduce energy delivered to the receiver and can increase the cost of generated energy	Tighter optical tolerances vs. field construction cost
[87]	PTC with ferrofluid and twisted-tape insert	Heat transfer and pumping power	Enhanced mixing improves heat transfer, but introduces additional flow resistance	Thermal enhancement vs. pressure drop and pumping demand
[55]	Thermocline vs. two-tank TES	Storage cost and discharge-temperature stability	Single-tank storage reduced investment and storage cost but lowered mean ORC efficiency in the evaluated case	Lower storage cost vs. temperature stability

rather than on maximum efficiency or concentration ratio alone[88,89].

Coccia et al.[88] developed and experimentally tested a low-cost PTC intended for industrial process heating. The collector consisted of a fiberglass support structure, extruded-polystyrene insulation, and an aluminum receiver protected by a low-iron glass cover. Experimental tests were performed with water at temperatures reaching 85°C. When thermal efficiency was plotted against the reduced temperature difference, the curve had an intercept of 0.658 and a slope of -0.683. The results indicate that this relatively simple PTC design can be used for industrial heating at moderate temperatures. Its performance under higher-temperature operating conditions, however, remains to be investigated. Ktistis et al.[89] tested a 288 m² PTC system connected to a steam generator and concrete TES at a soft-drinks production facility in Cyprus. In a separate operating mode, it stored 107.3 kWh of thermal energy. The two-month experimental campaign demonstrated how TES could help sustain steam delivery to industrial processes when solar irradiation becomes insufficient.

Bortolato et al.[90] investigated an asymmetric PTC developed for industrial process heating and direct steam generation. The collector used a flat aluminum bar-and-plate absorber fitted with an internal turbulator. With a concentration ratio of 42, it reached an overall thermal efficiency of up to 64% during steam generation under the specified reduced-temperature conditions, while pressure drop remained negligible. Generating steam directly in the collector can remove the need for intermediate heat-transfer loops, although steam quality and the stability of two-phase flow still require attention during system design. At the University of California, Merced, Widyolar et al.[91] tested a 45 m² XCPC array under three operating conditions: process heating, evaporation, and absorption cooling. The corresponding operating temperatures were approximately 70, 135, and 170°C, respectively. Annual simulations predicted thermal energy yields of 1,100 kWh/m² at 80°C and 700

kWh/m² at 160°C. The estimated levelized cost of heat was between 2 and 4 US cents/kWh. These results suggest that XCPC technology could provide an economically attractive solution for industrial processes operating at different temperature levels.

Galindo Luna et al.[92] carried out experimental tests on a 38.4 m² PTC field integrated with an ammonia–lithium nitrate absorption cooling system. The collector field delivered up to 6.5 kW of useful thermal power at operating temperatures reaching 105°C, with a peak thermal efficiency of 19.8%. The absorption chiller recorded an external coefficient of performance (COP) of 0.56 and achieved a minimum cooling temperature of 6°C. The results show the potential of PTC-based systems for solar-assisted air conditioning. Wang et al.[93] developed and validated a thermodynamic model of a double-effect LiBr–H O absorption cooling system driven by PTCs. Particular attention was given to the need to match the thermal energy supplied by the collector with the higher generator temperatures required by double-effect absorption chillers.

Tawfik et al.[94] designed a small-scale desalination unit based on a parabolic dish concentrator, using locally available recyclable materials to keep fabrication simple and affordable. System performance was investigated through experimental testing and numerical modeling, with the simulations predicting a maximum daily thermal efficiency of 36.04%. Beyond thermal efficiency, the practical value of this approach depends on the quantity of freshwater produced, the ability to maintain stable operation, and the overall cost of the installation.

Esfanjani et al.[95] investigated a dish-based solar desalination unit incorporating a humidification–dehumidification (HDH) process and a cylindrical–conical cavity receiver. The system was evaluated experimentally in Semnan, Iran, where the maximum freshwater production reached 0.966 L/day. Peak hourly exergy efficiency reached 14.04%, while collector thermal efficiency was 45.49%. Although dish-based systems have potential for desalination, their performance cannot be judged by collector efficiency alone. The amount of freshwater produced is equally important when assessing their practical value.

Roeb et al.[96] demonstrated a 100-kW pilot-scale STC for two-step thermochemical water splitting at the Plataforma Solar de Almería, Spain. The receiver–reactor incorporated iron-based mixed oxides coated onto ceramic honeycomb structures and operated under actual solar-tower conditions. The results demonstrated that solar hydrogen production through reversible redox reactions is feasible. They also showed that central-receiver systems can provide the high temperatures required for thermochemical processes. Thanda et al.[97] experimentally investigated a 250-kW ceria-based receiver–reactor for thermochemical hydrogen production using a large-scale solar simulator. Operating at temperatures of approximately 1,000–1,400°C, the reactor produced up to 8.8 g of hydrogen per cycle. This result indicates that central-receiver configurations can provide the high-temperature conditions required for hydrogen production and chemical energy storage. Thermal management, cycle duration, and heat recovery, however, remain important challenges for these applications.

The suitability of each collector technology depends on the thermal and operating conditions of the intended application. CPCs and XCPCs are suited to low- and medium-temperature applications, such as heating, drying, evaporation, and some cooling processes, particularly when a relatively simple optical design is desirable. PTCs are generally used for medium-temperature applications, including industrial heating, steam generation, and absorption cooling. Where higher levels of solar concentration and operating temperatures are needed, parabolic dish and central-receiver systems provide alternatives for more specialized applications, such as desalination and thermochemical hydrogen production. Collector efficiency alone is not sufficient for choosing among these technologies. The required process temperature and reliability of heat delivery must also be considered, along with generator-temperature requirements in cooling systems, freshwater production in desalination, and thermochemical-cycle performance in hydrogen production. Capacity, operating schedules, storage integration, and system-level energy and economic performance are also critical. Table 4 summarizes the suitability of CSCs for different thermal applications.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Technical and Operational Challenges: Although CSCs have undergone considerable technological development, several difficulties continue to affect their long-term efficiency, reliability, and economic viability. Optical losses, thermal degradation, material durability, heat-transfer-fluid stability, and the complexity of operating systems under changing environmental conditions remain among the main concerns.

Dust accumulation on mirror surfaces is a particular problem in arid regions. Dust and other contaminants on mirror surface gradually lower their reflectivity,

Table 4: Suitability of CSCs for Different Solar Thermal Applications

Ref.	Collector / system configuration	Solar thermal application	Main reported findings	Key technical considerations
[88]	PTCs	Industrial process heating	Tested at temperatures up to 85°C	Suitable for moderate-temperature heating
[89]	PTC with steam generator and concrete TES	Industrial steam production	940 L of steam/day; 107.3 kWh stored	Requires effective control and thermal storage
[90]	PTC with flat bar-and-plate absorber	Direct steam generation	Thermal efficiency up to 64%	Steam quality and two-phase flow stability
[91]	XCPC	Process heating, evaporation, and cooling	1,100 kWh/m^2·year at 80°C; 700 kWh/m^2 year at 160°C	Heat yield decreases at higher temperatures
[92]	PTC with ammonia–lithium nitrate absorption chiller	Solar cooling and air conditioning	Useful heat up to 6.5KW; COP up to 0.56	Requires suitable generator temperature
[93]	PTC with double-effect LiBr–H2O absorption system	Building cooling	Thermodynamic assessment of cooling performance	Depends on heat supply and cooling demand
[94]	PDC with desalination unit	Small-scale desalination	Predicted maximum daily thermal efficiency: 36.04%	Freshwater output and system cost
[95]	Parabolic dish with cavity receiver and HDH desalination	Freshwater production	Up to 0.966 L/day; exergy efficiency up to 14.04%	Limited production capacity
[96]	Central-receiver solar tower with thermochemical reactor	Solar hydrogen production	Demonstrated a 100 kW pilot-scale system	High-temperature operation and reactor durability
[97]	Central receiver with ceria-based reactor	Thermochemical hydrogen production	Up to 8.8 g H2 per cycle at 1,000–1,400°C	Thermal management and heat recovery

reducing the amount of solar radiation reaching the receiver and, consequently, the useful heat produced. Keeping the mirrors clean is not without cost, as it requires regular maintenance and may involve considerable water consumption. Anti-soiling coatings, automated cleaning systems, and sensor-based monitoring have been investigated as ways of reducing these problems [99,101].

High operating temperatures place considerable demands on both insulation and the materials used in collector systems. Heat losses from receivers, piping, and storage units reduce the energy available for practical applications. Repeated exposure to heating and cooling cycles can gradually weaken collector components, leading to mechanical fatigue, deterioration of protective coatings, and material degradation. Molten-salt systems are subject to further operational difficulties, notably corrosion and the possibility of salt freezing within the system. These risks make material compatibility, thermal insulation, and temperature regulation important design considerations. Particular attention is also required during startup and shutdown, when inadequate temperature control can increase the likelihood of component damage[98,102].

Prolonged exposure to high temperatures can compromise HTF stability during extended operation. Extended exposure to heat may alter their properties, affecting heat-transfer performance and viscosity, as well as the pumping power needed to maintain circulation. Modified receivers and nanofluids may improve heat transfer, but the associated increase in hydraulic resistance can also raise auxiliary energy consumption. Their benefits must therefore be evaluated through integrated thermal–hydraulic and operational assessments.

Variable DNI, ambient temperature, and wind conditions further complicate stable thermal energy delivery and system control. The use of TES alongside predictive control, precise solar tracking, and continuous performance monitoring can make system operation more flexible and help reduce fluctuations in performance during changing operating conditions.

Economic and Practical Limitations: The financial burden of CSC projects extends well beyond the purchase of the collector itself. Reflector and receiver fabrication, tracking equipment, TES units, and control systems all contribute to the initial investment. Once installed, the plant also requires continuous expenditure on operation and upkeep, particularly for mirror cleaning and the replacement or servicing of worn components. Whether a project is economically viable depends partly on the conditions at the installation site, including DNI, access to land and water, and the temperature level required by the intended application.

Adding TES changes both the cost structure and the operating capabilities of a solar thermal plant. Although stored heat can be used when solar irradiation falls, storage equipment requires additional investment and introduces heat losses that reduce the energy ultimately available for use. Advanced materials and heat-transfer modifications may offer further improvements, but their

durability under prolonged operation and their economic justification have not yet been established. A realistic economic assessment must therefore extend beyond initial capital expenditure and peak efficiency to include maintenance and operating costs, storage capacity, component service life, and the total useful energy delivered over the plant's lifetime[79, 81, 83].

Future Research Opportunities: Future development should concentrate on three persistent weaknesses of CSC technology: receiver degradation, optical and thermal energy losses, and the financial burden of incorporating TES. Further investigation is also needed into advanced HTFs, PCMs, and materials with improved corrosion resistance. Before these alternatives can be considered viable for industrial deployment, their ability to retain their thermal properties, structural integrity, and operational stability over extended periods must be demonstrated. Beyond material and design improvements, artificial intelligence, predictive control, and automated cleaning offer opportunities to improve system operation and reduce the burden of routine maintenance. Before these approaches can be adopted commercially on a larger industrial scale, their long-term performance must be tested experimentally under realistic operating conditions, with techno-economic assessments covering the costs and benefits involved[98–102].

CONCLUSIONS

This review examined the optical and thermal performance, technical features, operating limitations, and suitability of major CSC technologies for different applications. The technologies considered were PTCs, LFRs, PDCs, central-receiver systems, and CPCs. The comparison showed that none of these technologies performs best under all conditions. Their relative performance varies with operating temperature, available solar resources, receiver design, optical accuracy, and the requirements of the intended application. PTCs are suitable for medium- and high-temperature process heating and CSP applications. The choice of collector technology depends largely on the thermal requirements and practical constraints of the intended application. Where low construction costs and straightforward installation are priorities, LFRs offer an attractive option. CPCs, with their less demanding optical and tracking arrangements, are generally used in processes requiring low- to medium-temperature heat. Applications involving higher thermal demands, including specialized electricity generation and thermochemical processes, are better suited to parabolic dish and central-receiver systems, which can achieve substantially higher concentration ratios and operating temperatures. Meaningful comparisons between these collector technologies are difficult because published studies do not use consistent test conditions, evaluation methods, or system boundaries. Consequently, reported performance values cannot always be compared directly, and differences in methodology must be accounted for before drawing conclusions about their relative efficiency. These factors must be accounted for before making meaningful judgments about their relative performance. TES, particularly systems using PCMs, offers a means of maintaining a more stable heat supply and extending system operation beyond periods of sufficient solar irradiation. Other approaches, including nanofluids, modifications to receiver geometry, and changes to heat-transfer surfaces, have also been investigated as means of improving thermal performance. Such improvements are not without drawbacks. Additional investment, greater hydraulic resistance, higher pumping requirements, and material-compatibility problems may reduce their practical value. Their effects need to be assessed at the level of the complete system rather than through individual performance measures. Several problems continue to affect the long-term operation of concentrating solar systems. Mirror soiling and tracking errors reduce the amount of radiation intercepted, while receiver heat losses, material degradation, molten-salt corrosion, and heat-transfer-fluid instability can affect thermal performance and reliability. Dealing with these problems calls for more durable materials, improvements in optical and thermal design, effective cleaning methods, dependable control strategies, and thermal storage arrangements that remain economically practical. The successful use of concentrating solar technologies depends on selecting collectors and operating strategies that meet the needs of each application, rather than pursuing the highest value of a single performance indicator. Long-term experimental studies under realistic operating conditions are still needed, together with standardized performance assessments, combined energy and exergy analyses, and detailed techno-economic evaluations. These investigations will help establish the reliability, economic practicality, and scalability of solar thermal systems used for industrial heating, steam generation, cooling, electricity generation, and high-temperature chemical processes.

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