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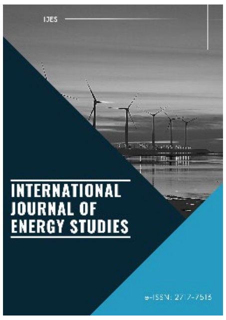

Erratum Article

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Erratum to: A comprehensive review of concentrated solar power technologies: Operating principles, efficiency analyses, and energy storage capabilities of tower, parabolic trough, Dish-Stirling, and Fresnel systems

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In the article titled "A comprehensive review of concentrated solar power technologies: Operating principles, efficiency analyses, and energy storage capabilities of tower, parabolic trough, Dish-Stirling, and Fresnel systems", published in Volume 10, Issue 4 of the International Journal of Energy Studies, a formatting problem occurred in the published version of the manuscript.

During the typesetting process, some bibliographic and publication information fields in the manuscript were incorrectly rendered due to formatting issues in the source document. In particular, the page number range in the article information section, the page number range in the citation information and the page number range in the article header section were displayed incorrectly as placeholder text in the published version.

The editorial office reviewed the article and corrected the layout, bibliographic information, citation information, and publication date fields in accordance with the journal's template.

The scientific content of the article remains unchanged. The correction concerns only formatting, bibliographic information, citation display, and header information.

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Original article file can be found here: dergipark.org.tr/en/download/article-file/5043569

The corrected version of the article is provided below.

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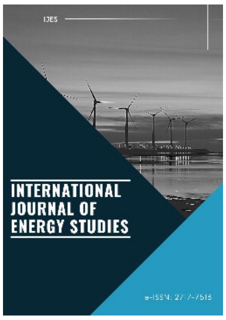

Review Article

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A comprehensive review of concentrated solar power technologies: Operating principles, efficiency analyses, and energy storage capabilities of tower, parabolic trough, Dish-Stirling, and Fresnel systems

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Highlights

- CSP technologies are critically reviewed in terms of working principles, efficiency, and storage integration.
- Comparative assessment covers tower, parabolic trough, dish-Stirling, and Fresnel systems.
- Advances in heat transfer fluids, optical tracking, and AI-based control significantly improve CSP performance.
- Integration of thermal energy storage enables dispatchable and stable solar electricity production.

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ABSTRACT

The rapid increase in global energy demand, the finite nature of fossil fuel resources, and the onset of climate instability have collectively accelerated the development of renewable energy technologies and rendered the transition to these alternatives inevitable. In this context, Concentrated Solar Power (CSP) systems have emerged as a compelling alternative technology by offering thermal energy storage capabilities and the potential for uninterrupted electricity generation. The effectiveness of these systems extends beyond the high temperatures achieved through solar concentration; thanks to their energy storage capabilities and operational flexibility, CSP technologies are increasingly able to compete with fossil-fuel-based power plants. CSP systems can generate electricity during daylight hours and, through integrated thermal storage units, continue to supply power at night or under suboptimal solar conditions. These features enhance energy security and contribute significantly to decarbonization targets in power generation. This review comprehensively examines various CSP technologies, including power tower systems, parabolic trough collectors, dish-Stirling engines, and linear Fresnel reflectors. The fundamental working principles, thermal energy storage methods, and efficiency levels of each system are discussed in detail. Furthermore, the advantages and limitations of each CSP technology are evaluated. In conclusion, with advancements in heat transfer fluids, optical tracking systems, and AI-assisted control technologies, CSP systems are projected to play a strategic role in large-scale renewable energy production and become a reliable source of baseload power in the future.

Keywords: Concentrated solar power (CSP), Solar power tower, Parabolic trough, Dish-Stirling system, Fresnel reflector, Thermal energy storage, sCO_2 Brayton cycle, Renewable energy.

1. INTRODUCTION

Global energy consumption has shown a dramatic increase in recent years, primarily driven by industrialization, urbanization, and digitalization. This growing demand for energy production has deepened the dependence on fossil fuels while simultaneously accelerating greenhouse gas emissions and climate change. In this context, the transition to sustainable and low-carbon energy systems has become not only an environmental imperative but also an economic and political necessity. Solar energy, due to its inexhaustible, clean, and widely accessible nature, stands out as one of the most prominent options among renewable energy sources. With the exception of geothermal and tidal energy, all other renewable energy sources on Earth fundamentally rely on solar energy [1]. Given the environmental impacts of fossil fuel-based energy systems particularly their contribution to global climate change through greenhouse gas emissions photovoltaic systems and concentrated solar power (CSP) technologies have gained increasing prominence.

Among these, photovoltaic systems are particularly significant as a clean and renewable alternative energy source [2, 3]. In the years following the discovery of photovoltaic cells, various technological advancements have been achieved, with a particularly notable and significant increase in power conversion efficiencies observed since 1996 [4]. Photovoltaic (PV) systems are widely used today due to their ability to convert sunlight directly into electricity, offering several advantages such as portability, modularity, and low operating costs. However, since PV systems rely on sunlight for electricity generation, they are unable to produce energy during nighttime. Moreover, the amount of electricity generated can vary significantly depending on the season and even the time of day [5]. This poses a significant disadvantage in terms of grid reliability and maintaining the supply-demand balance. Furthermore, the need for energy storage in photovoltaic systems substantially increases the overall system cost.

According to reports by the International Energy Agency (IEA), the 420 GW of solar capacity installed in 2023 represents a doubling of global capacity compared to 2022. Remarkably, this increase alone is equivalent to the total global solar capacity installed throughout the entire year of 2022 [6]. Concentrated Solar Power (CSP), which uses mirrors or lenses to concentrate a large area of sunlight onto a small area, technologies are emerging as a serious alternative to photovoltaic (PV, systems that directly convert sunlight into electricity via semiconductor materials) systems.

In this context, CSP systems are gaining significance not only for their ability to generate electricity from solar energy, but also for their thermal energy storage (TES, technologies that store excess thermal energy for later electricity generation typically using molten salts, phase change materials, or other media) capabilities. CSP systems utilize reflective optical components to concentrate sunlight onto a small area, transferring thermal energy at high temperatures to heat transfer fluids (HTFs, specialized working fluids that absorb, transport, and release thermal energy) or directly to Stirling engines. This thermal energy is then used to generate electricity either indirectly via steam turbines or directly via Stirling engines. One of the key advantages of CSP systems is their ability to be integrated with thermal storage technologies, allowing for continuous power generation even during periods without solar irradiance. This feature makes CSP systems a reliable energy source during peak demand periods. Currently, four main types of CSP technologies have been developed: solar power towers, parabolic trough collectors, dish-Stirling systems, and linear Fresnel reflectors. **Table 1** summarizes the key performance indicators of different CSP technologies, including solar-to-electric efficiency, projected CAPEX, and land-use efficiency.

Table 1. Comparative overview of major CSP technologies, including efficiency, projected capital costs (CAPEX), and land-use efficiency (LUE).

CSP Technology	**Efficiency (Solar-to-Electric)**	**CAPEX ($/kWe, Projected Trend)**	**Land-Use Efficiency (LUE)**
Parabolic Trough	~15% collector-to-grid net efficiency; typical values in CSP plants like SEGS and Solana[7]	2020:~6,280$/kWe; 2030:~4,379$/kWe; 2050:~3,928 $/kWe[8]	Higher land requirement than LFC, but higher collector efficiency (~180–190 kWh/m²). Suitable for medium-to-large scale deployment [9]
Power Tower	~24.5% [10]	~6.000–9.000 $/kWe[11]	Moderate: Requires centralized heliostat field; higher temperatures (molten salt, ~565 °C).
Dish–Stirling	~23.7% [12]	~3000-10,000 $/kW	High: Compact units allow better land use; however, commercial penetration is low and TES integration is challenging [13].

Each system employs different engineering approaches in terms of solar collection, concentration, heat conversion, and power generation. Solar tower plants enable highly efficient power cycles by achieving temperatures up to 600–1000 °C via thousands of heliostats directed at a central receiver. Parabolic trough systems operate at lower temperatures but offer cost-effective electricity production. Dish-Stirling systems demonstrate the highest efficiency among CSP technologies, although they have not yet been widely adopted due to economic limitations. Linear Fresnel systems stand out for their cost-efficiency and compact design. Each CSP technology has its unique advantages and engineering characteristics. This study provides a comprehensive overview of the fundamental principles of CSP technologies, the current system types, thermodynamic performance analyses, and energy storage capabilities.

The engineering parameters, benefits, limitations, and practical feasibility of each plant type are examined, along with the integration potential of advanced cycle technologies and next-generation materials. The aim of this work is to assess the role of CSP systems in sustainable energy transitions and to offer a scientific framework that can guide future research and development in the field. For this review, a comprehensive literature survey was conducted using Web of Science, Scopus, and Google Scholar databases. The search was limited to the years 2000–2025, and only peer-reviewed journal articles were considered. Inclusion criteria focused on studies addressing the fundamental operating principles of CSP systems, thermodynamic performance analyses, thermal energy storage integration, and environmental impacts. Publications that were out of scope or lacked sufficient technical detail were excluded.

This approach was adopted to ensure methodological transparency and to provide a balanced and systematic overview of the field. This review is structured as follows: Section 2 examines solar power tower (SPT) plants; Section 3 analyzes parabolic trough collector (PTC) systems; Section 4 discusses dish-Stirling configurations; Section 5 evaluates linear Fresnel reflector (LFR) systems; and Section 6 surveys Fresnel lens collectors and relevant material/manufacturing aspects. Section 7 provides a cross-cutting discussion that compares thermodynamic performances, thermal energy storage (TES) options, environmental and water-use impacts, techno-economic considerations, and deployment constraints across CSP technologies. Finally, Section 8 summarizes the key findings and outlines future research directions.

2. SOLAR POWER TOWER PLANTS

Solar power tower plants (SPTs) are among the most promising types of CSP technologies in terms of scalability and efficiency enhancement potential. The high temperatures achieved in SPTs allow for the Rankine cycle to operate with greater thermal efficiency. Steam generation at elevated temperatures enables conventional steam turbines to function more effectively and with improved performance [14, 15]. One of the most critical components in solar power tower plants (SPTs) is the heliostat mirrors. Each heliostat is angularly positioned to focus sunlight onto a single point known as the central receiver tower, using motorized tracking systems that enable movement along both horizontal and vertical axes. The orientation of these mirrors is continuously adjusted in real-time by a central control system in response to the sun's changing position throughout the day.

This ensures that the mirrors are always aligned at optimal angles for maximum efficiency of the SPT. Typically, the heliostats are arranged in a circular configuration around the central tower. The surface area of individual heliostats generally ranges from 10 to 100 m^2. They are coated with high-reflectivity glass (reflectance >94%) and exhibit targeting accuracies in the milliradian range [16, 17] In next-generation heliostat systems, control algorithms supported by artificial intelligence are utilized to increase energy output while simultaneously minimizing maintenance requirements[18]. Heliostats account for approximately 50% of the total system cost[19]. Numerous recent studies focus on reducing these costs through structural lightweighting, minimizing the number of servo motors, and enabling mass production [20].

Although various parameters influence the performance of central tower solar power plants, tower height is among the most critical. It directly affects optical losses such as shading, blocking, cosine losses, and atmospheric attenuation. Moreover, it plays a significant role in defining the boundaries and layout of the heliostat field [21]. Although smaller towers were used in initial pilot implementations, central tower solar power plants (SPTs) with heights reaching up to 205 meters have now been constructed [22, 23].

Central tower solar power plants (SPTs) are among the CSP technologies capable of reaching the highest operating temperatures. With this technology, temperatures of approximately 700 °C can be achieved [24, 25]. The increase in operating temperature enables the use of more efficient thermodynamic cycles, such as the Brayton cycle. These systems are well-suited for large-scale projects and allow for high-capacity installations over expansive areas.

In particular, SPTs offer an ideal solution for large power plants in regions with high solar irradiance, such as desert areas. Furthermore, due to their scalability, SPTs provide several advantages over other CSP technologies [26, 27]. The concentration of energy at a single point shortens the energy transfer path, thereby reducing losses and improving the overall efficiency of the plant. Compared to parabolic trough CSP systems, SPTs are capable of achieving higher temperatures.

Additionally, the relatively simpler control mechanisms of tower systems create favorable conditions for thermal energy storage. As a result, tower-type systems are among the most suitable options for large-scale power generation [28]. However, the design and installation costs of SPTs can be higher than those of other CSP systems. These elevated initial investments may be offset in the long term by higher efficiency and lower operational costs. Advancements in materials science continue to enhance the performance of tower-type systems.

Recently developed materials enable SPTs to operate at higher temperatures and achieve more efficient energy conversions. Ceramic-based receiver materials, in particular, stand out as ideal solutions due to their high thermal resistance and low thermal expansion coefficients [29]. SPTs can be broadly classified into two main categories: systems with thermal energy storage and those without. **Figure 1** illustrates the key operating principle and layout of a solar power tower (SPT) system, highlighting heliostats, the central receiver, thermal storage, and the steam turbine cycle.

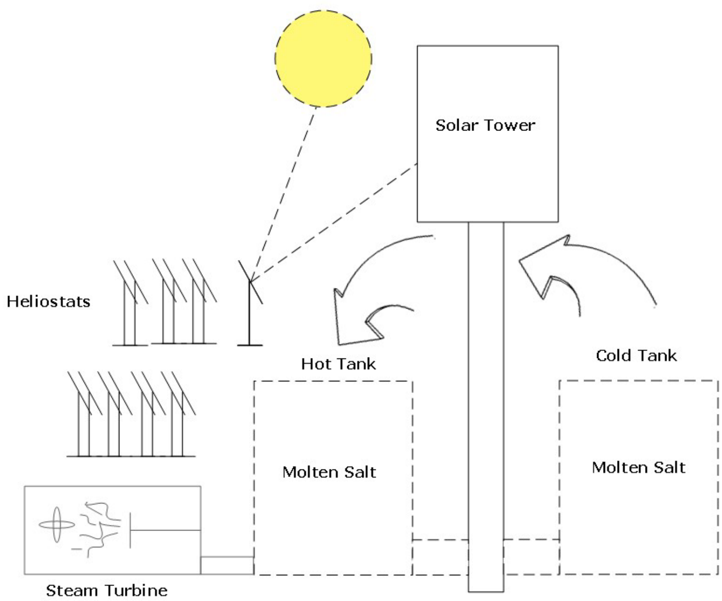

Figure 1. Schematic representation of a typical solar power tower (SPT) system.

The figure illustrates the main components and operating principle of the technology: an array of heliostats focuses incoming solar radiation onto a central receiver mounted on a tower, where heat is transferred to a working fluid typically molten salt. The heated molten salt is stored in a hot tank and can be used to generate steam on demand, driving a steam turbine for electricity production. After transferring its heat, the cooled salt is cycled back to the cold tank to repeat the process. This configuration enables both real-time electricity generation and thermal energy storage for dispatchable power supply, including nighttime operation.

In these plants, minimizing optical losses, protecting reflective surfaces from performance-degrading factors such as soiling and abrasion, and ensuring that incoming solar rays are accurately directed toward the tower all require regular and meticulous maintenance. Another critical factor enabling operation at such high temperatures is the choice of heat transfer fluids. In tower-type systems, various heat transfer media are used. Among these, air allows for the most straightforward heat transfer from the receiver to the turbines; however, due to its low thermal conductivity and density, its efficiency is limited, and it requires high operating pressures at pipe junctions.
Water, on the other hand, undergoes instantaneous phase change to steam in the tower, offering a higher heat transfer coefficient. Nevertheless, the high pressure of superheated steam makes it difficult to control. Steam-based systems face challenges such as high pressure and corrosion, which significantly limit their thermal storage capacity; these systems typically allow for only up to two hours of storage, making them unsuitable for long-duration thermal energy storage. In contrast, one of the main advantages of SPTs is their compatibility with thermal energy storage systems. This integration enables continued electricity production after sunset and ensures stable system operation. In systems equipped with thermal storage, electricity generation can be extended into nighttime hours, resulting in higher total daily electricity output compared to non-storage systems. One of the most widely adopted methods in thermal energy storage applications is the two-tank molten salt system, consisting of separate hot and cold tanks.

In this setup, the heat transfer fluid is drawn from the cold tank and sent to the receiver at the central tower, where it is heated by solar irradiation. The heated fluid is then stored in the hot tank and later transferred to the turbine system for electricity generation. The high-temperature fluid stored in the hot tank remains available for steam generation and electricity production when needed. For the commonly used $NaNO_3$–KNO_3 based 'Solar Salt' mixture, the cold tank temperature is typically maintained at approximately 290 °C, while the hot tank temperature reaches around 565 °C [30]. In thermal storage systems, heat energy is stored either as high-pressure steam or in the form of molten salts. Waste heat that cannot be used immediately is stored for later use during periods of demand. The heated working fluid is stored in a hot tank and, when energy is needed, it is used to generate steam, which drives a turbine to produce electricity. This storage technology enables energy retention for periods ranging from 8 to 15 hours. Recent advancements in energy storage systems have contributed to significant cost reductions [31]. Phase change materials (PCMs) are media that store and release thermal energy via latent heat during reversible phase transitions at nearly constant temperature. Additionally, some systems are being developed using PCMs, offering compact and high-density energy storage solutions [18]. The high-temperature fluid withdrawn from the storage tank is converted into superheated steam via a heat exchanger.

However, in the event of a system malfunction, the heating mechanism may be deactivated, posing the risk of salt solidification within pipes and pumps. Under normal operating conditions, the salt is kept in a molten state through continuous heating using electric heaters. On the other hand, due to the large volumes of salt stored in the tanks, any potential leakage can pose serious environmental risks. The performance of SPTs is directly influenced by their geographic location. Regions with high solar irradiance and low cloud cover maximize the efficiency of this technology. While these systems are noteworthy for their high-temperature energy production and thermal storage capacity, they also present several technical, environmental, and economic challenges.

In particular, large-scale installations may negatively affect natural habitats, making ecologically sensitive planning processes essential. Furthermore, the high installation costs represent a significant economic disadvantage. One of the most critical drawbacks of these systems is the relatively high freezing point of molten salt, around 290 °C, which necessitates continuous energy input to maintain the salt in its liquid state. Moreover, STPs require substantial water resources, particularly in facilities that utilize wet cooling systems. The high-water consumption in such systems can render this technology unsustainable in regions already under water stress. From an environmental standpoint, the extensive land requirements may lead to the degradation of natural habitats and a decline in biodiversity.

Concentrated solar radiation also poses a serious threat to birds flying near the tower, often resulting in avian mortality. Maintenance and operational processes are complex, requiring precise alignment of heliostats and regular cleaning of their reflective surfaces to prevent a decline in reflectivity. Additionally, leakage of molten salts or other chemicals can contaminate soil and water sources, thereby increasing environmental risks. All these factors may limit the feasibility and sustainability of STPs systems [32-37]. In conclusion, due to their ability to enable high-temperature energy conversion, support thermal storage, and integrate with hybrid systems, STPs play a pivotal role in renewable energy generation. In the future, advancements in materials science, improvements in system efficiency, and reductions in capital costs are expected to further increase the share of STP technology in the energy sector.

The design and operational infrastructure of STPs continues to evolve with annually updated engineering solutions. Although initial investment costs still appear higher than those of parabolic trough systems, breakthroughs in materials science and automation are rapidly narrowing this cost gap. Projections suggest that, alongside photovoltaic fields, tower-based concentrating systems will become one of the leading solar energy technologies in the near future.

3. PARABOLIC TROUGH SOLAR POWER PLANTS

Parabolic trough collectors (PTCs) are among the most commonly used technologies in both industrial and academic contexts within the field of concentrated solar power (CSP). These systems operate by utilizing curved parabolic reflector surfaces to concentrate incoming solar radiation along a focal line. A receiver tube placed at this focal line contains a circulating heat transfer fluid (HTF), which is heated as it absorbs the concentrated solar energy. Through this solar concentration mechanism, direct solar irradiance is elevated to high temperatures and converted into thermal energy, which can then be used in mechanical and electrical power generation processes. This heat is typically transferred using thermal oils, which are then used to produce pressurized steam and subsequently converted into electricity. In parabolic trough CSP systems, the temperature of the working fluid can exceed 500 °C, which presents a significant advantage for steam power cycles.

When thermal oil is used as the HTF, the maximum achievable operating temperature is around 400 °C. In industrial process heating (IPH) applications, the working fluid typically operates within a temperature range of 100–250 °C, making PTC systems suitable for low-temperature public applications such as district heating and domestic hot water supply [38]. The thermal efficiency of parabolic trough collector systems is influenced by a variety of physical and geometrical parameters. A comprehensive analysis of these parameters particularly the pressure drop within the system, heat transfer mechanisms, and the overall thermal performance of the collector is essential. Energy losses in these systems are generally categorized as optical losses, thermal losses, and cosine losses. The efficiency of PTC systems is closely linked to the precise design of the reflector geometry, the optical properties of the reflective material, the absorptivity/emissivity balance of the receiver tube, and the thermophysical properties of the working fluid. The receiver tube, a core component of the system, is typically manufactured from steel or copper with selective coatings, and is enclosed in a vacuum-sealed glass envelope to minimize thermal losses [39].

Optical losses are primarily associated with the reflectance and transmittance characteristics of the reflector surfaces and the glass cover materials. Meanwhile, the temperature difference between the absorber tube and its surrounding environment results in thermal losses due to conduction and convection heat transfer mechanisms. Moreover, when the angle of incidence of solar radiation deviates from normal incidence on the collector surface, cosine losses occur. All of these parameters must be carefully evaluated during the design process to ensure that Parabolic Trough Collector (PTC) systems operate at optimal performance [40].

The absorber tube must be positioned at an appropriate distance from the reflectors to maximize energy transfer. Surface coatings that exhibit high solar absorptance while maintaining low thermal emittance are critical for reducing radiative losses. The most commonly used heat transfer fluids (HTFs) in collectors include synthetic thermal oil [41], water [42], stream [43], air [44] and, increasingly in recent years, nanofluids. Nanoparticle additives (e.g., Al_2O_3, CuO, TiO_2) provide higher thermal conductivity, lower viscosity, and enhanced convective heat transfer coefficients compared to conventional fluids [45, 46]. This enables greater heat transport with reduced pumping power, thus improving overall system efficiency. In addition to fluid selection, enriching the flow structure with turbulence is an important strategy for enhancing PTC system efficiency [47].

Incorporation of turbulators or helical inserts inside the absorber tube reduces the boundary layer thickness and increases interaction between the fluid and heat transfer surface. These improvement strategies, supported by geometric modifications and guided flow patterns, have the potential to enhance thermal transfer efficiency without significantly increasing pressure drop[48]. Solar tracking systems are another key factor directly influencing the energy collection capacity of PTC systems. Typically employing single-axis trackers, these systems align the reflector perpendicular to the sun throughout the day to optimize incident irradiance. This approach, previously investigated in photovoltaic cells, has the potential to yield a 20–30 % increase in annual energy gain compared to fixed collectors [49].

PTC systems especially when integrated into industrial process heating or water purification applications offer significant potential to reduce carbon emissions. Through careful selection of geometric parameters, advanced fluid technologies, innovative modeling techniques, and integration of tracking systems, these systems may find practical application in both energy generation and environmental sustainability. Heat transfer oils commonly used as HTFs must exhibit high heat transfer coefficients and low viscosity, while also maintaining relatively high freezing points. The thermal balance inside the absorber tube in alignment with the focal line of the parabolic mirror must be precisely controlled, since these oils may pose a risk of ignition or explosion at elevated temperatures. Due to the use of oils as the primary heat transfer medium, the maximum temperature in PTCs is typically lower than that of other CSP technologies, resulting in reduced thermodynamic efficiency. However, thermal energy storage systems similar to those used in central receiver systems can be integrated into this type of plant [50-52]. The geometric design of parabolic mirrors inherently causes optical losses, as not all incident solar radiation is directed exactly to the focal line.

Moreover, their curved geometry demands a larger land area compared to central receiver systems, presenting a disadvantage in terms of land use. Nevertheless, despite their comparatively lower energy conversion efficiency, the lower manufacturing and installation costs of parabolic trough systems play a significant role in their selection. In conclusion, parabolic trough solar collectors represent a complex yet optimizable class of renewable energy power plants, situated at the intersection of optics, thermodynamics, materials science, and control systems.

4. DISH-STIRLING SYSTEMS

The primary characteristic of the parabolic dish collector in Dish-Stirling systems is its ability to efficiently capture and concentrate solar radiation onto a focal point. The dish configuration enables the concentration of sunlight onto a small area with high intensity. This advantage, when combined with the integration of Stirling engines, allows for high-efficiency electricity generation at temperatures exceeding 1000 °C [53]. Among concentrated solar power technologies, Dish-Stirling systems achieve the highest efficiency in electricity generation. The key to this performance lies in the ability of the dish-shaped mirrors to concentrate solar radiation onto a small focal point, thereby delivering a high energy flux to the Stirling engine [54].

Figure 2 illustrates the basic configuration and working principle of a dish-Stirling concentrated solar power (CSP) system. The parabolic dish reflector collects and focuses incident solar rays onto the focal point, where the Stirling engine is positioned. At this point, concentrated solar energy is converted into mechanical power, which can subsequently be used for electricity generation. The diagram also shows the support tower and key optical pathways involved in the system.

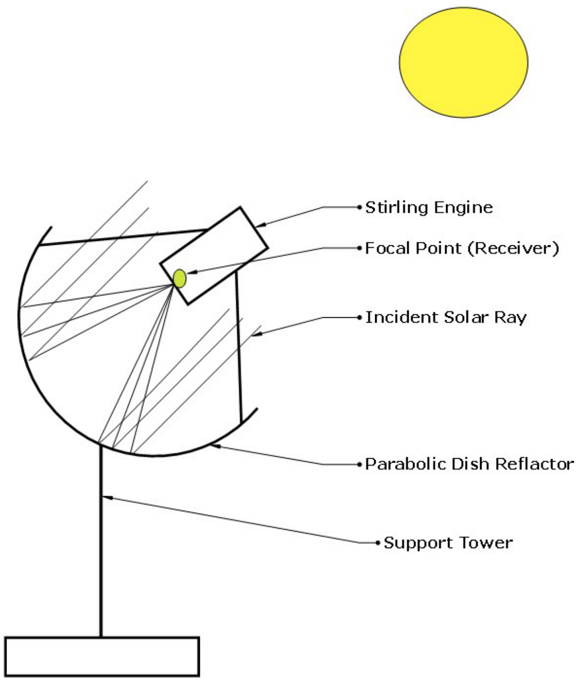

Figure 2. Schematic of a dish-Stirling CSP system, highlighting solar concentration onto the focal point and direct conversion of thermal energy to mechanical work by the Stirling engine.

The high temperature generated by the concentrated solar radiation is directly converted into mechanical energy by the Stirling engine located at the focal point of the parabolic dish. To ensure continuous and high-efficiency operation, the mirrors must precisely track the sun's position throughout the day. Particularly, maintaining a perpendicular incidence angle of sunlight onto the dish maximizes the electricity output from the Stirling engine. The diameter of the parabolic dish plays a crucial role in determining the amount of energy collected; as the diameter increases, the heat accumulated at the focal point also increases, allowing the use of more powerful Stirling engines. In addition to conventional parabolic dishes, alternative architectures using flat mirror panels to collect sunlight and concentrate it at the rear of the system have been experimentally evaluated to enhance Stirling engine performance.

Stirling engines are among the most effective options for converting thermal energy into mechanical work. In a Stirling engine, the working gas inside the engine expands upon receiving heat from an external source. This expansion generates pressure that drives the pistons, thereby converting external heat into mechanical energy. As an external combustion engine, the Stirling engine (SE) offers several advantages, including low emissions, low maintenance, reduced noise and vibration, theoretically high thermal-to-electric efficiency, and fuel flexibility, making it particularly suitable for residential combined heat and power (CHP) applications [55]. Stirling Engines in Dish-Type Concentrated Solar Power Systems: Configurations, Advantages, and Limitations Stirling engines are external combustion engines that operate solely using externally supplied heat energy, based on the Carnot cycle. They are capable of utilizing diverse heat sources such as waste heat, concentrated solar energy, or plutonium, making them particularly suitable for dish-type concentrated solar power (CSP) systems.

Stirling engines are categorized into three main configurations alpha, beta, and gamma based on the arrangement of their internal pistons. In alpha-type Stirling engines, the pistons are located in separate cylinders and operate with a 90° phase difference, resulting in high power density; however, this design is more susceptible to heat losses [56, 57]. In beta-type engines, the displacer and the power piston move along the same axis within a single cylinder, offering a compact structure and efficient heat transfer [58]. Gamma-type engines operate similarly to beta-type but have the displacer and power pistons located in separate cylinders, enabling mechanical decoupling and thereby reducing friction and vibration during operation [59, 60]. Each configuration presents specific advantages and limitations depending on the application area, with selection criteria in micro-cogeneration systems being shaped by technical requirements [61]. However, several critical drawbacks limit the widespread deployment of dish-Stirling systems. These systems can only utilize direct solar irradiation and are therefore unable to harness diffuse solar radiation. This constraint confines the efficient operation of the system to regions with high solar irradiation potential, while significantly reducing performance under variable weather conditions. Additionally, the requirement for high-performance materials capable of withstanding temperatures exceeding 1000 °C increases both the initial capital investment and the frequency and cost of maintenance.

Since Stirling engines must operate under a delicate thermal balance, sudden temperature fluctuations or transient shading can lead to unstable system behavior. Furthermore, the dish structure must continuously track the sun at an optimal angle, necessitating the integration of precise and energy-intensive solar tracking mechanisms. The risk of malfunction and the ongoing maintenance needs of these tracking systems pose potential threats to system reliability, particularly under prolonged outdoor operating conditions. The high number of moving components, especially those exposed to elevated temperatures, can suffer from material degradation over time, thereby limiting the operational lifespan and performance consistency of the system. Due to the currently high production costs, this technology is not yet employed in large-scale power generation facilities. As a result, such systems are mostly utilized within research and development projects, pilot-scale implementations, or in specially tailored applications. Nevertheless, ongoing research is focused on developing cost-reducing and efficiency-enhancing technological improvements to support wider deployment.

5. LINEAR FRESNEL COLLECTORS

Linear Fresnel Reflectors (LFRs) have emerged in recent years as one of the key technologies among CSP systems due to their cost-effectiveness and structural simplicity. LFR systems utilize flat or slightly curved mirrors arranged in a linear configuration to concentrate sunlight onto a fixed receiver tube positioned centrally above the reflectors. The concentrated radiation increases the temperature of the working fluid or air flowing through this tube. In terms of operating principle, these systems function on a logic similar to that of parabolic trough solar power plants [62]. Compared to parabolic trough systems, linear Fresnel collectors offer several practical advantages. The use of flat reflective surfaces not only simplifies the manufacturing processes but also significantly reduces overall system costs. Due to their relatively low structural height, the amount of material required for construction and installation is also minimized, allowing for economical and lightweight solutions.

In addition to fixed-position designs, advanced variants with dual-axis tracking capabilities have also been implemented. Currently, research and development efforts aimed at improving the performance of linear Fresnel collector technology are actively ongoing [63-65]. Another advantage of linear Fresnel collectors is their mechanically simpler design compared to parabolic

trough systems, owing to their ability to operate either in a fixed position or with single-axis tracking. This simplicity facilitates easier automation and enhances operational manageability.
The flat mirrors used in LFR systems are considerably cheaper and easier to manufacture and install than the curved mirrors employed in parabolic trough systems. Moreover, the flat configuration experiences lower wind loads, which allows for the use of lighter supporting structures. Consequently, both structural costs and maintenance requirements are reduced. With direct air-heating configurations, these systems can achieve stable air outlet temperatures in the range of 300–400 °C [66]. Lens-based Fresnel systems can achieve thermal efficiencies of up to 50% [67]. Moreover, due to the lower focusing precision of flat mirrors compared to parabolic systems, linear Fresnel reflectors are more prone to optical aberrations. This can lead to non-uniform heat distribution across the absorber tube. Such thermal imbalance not only reduces overall thermal efficiency but can also induce thermal stresses on the absorber material. In the absence of secondary reflector systems, optical losses further increase. Since the absorber tube is typically located above the mirror field, convective and radiative heat losses are comparatively higher. Additionally, the use of flat mirrors limits tracking accuracy, making it more challenging to maintain optimal solar concentration throughout the day compared to parabolic trough systems. For high-temperature applications, thermal efficiency decreases, and it becomes more difficult to achieve a stable temperature profile in the heat transfer fluids. One of the major limitations encountered in LFR technology is the potential for mutual shading or light-path interference due to the close placement of adjacent reflectors. To mitigate this effect, the length of the absorber tube can be increased; however, this strategy results in higher overall system costs [68].

6. FRESNEL LENS COLLECTORS

Fresnel lenses are a type of lens developed as an alternative to traditional glass lenses. Their role in CSP applications is being explored as a means to enhance system efficiency through low-cost and flexible designs [69-71]. Fresnel lenses are significantly lighter, more flexible, and more economical to manufacture than conventional glass lenses. The first Fresnel lens was designed in 1822 by the French scientist Augustin Fresnel as an innovative solution to improve the light performance of lighthouses. The first plastic-based Fresnel lens was produced in 1951 by Miller and his colleagues [71, 72]. For many years following their invention, Fresnel lenses were made from glass using traditional casting methods with metal molds. However, in the past four decades, advancements in molding and pressing technologies have enabled the production of Fresnel lenses with superior optical properties using computer-controlled techniques and a variety of materials.

Fresnel lenses can be fabricated from a range of raw materials with different physical and chemical properties.
The choice of material depends on several factors, including operating temperature, optical transmittance, mechanical strength, and production cost. Among the most commonly used materials are acrylic [73], polycarbonate [74, 75] and rigid vinyl [76]. Historically, Fresnel lenses have been employed in a wide array of applications, ranging from lighthouses and portable magnifiers to projection devices and solar concentrator systems. More recently, ultra-thin Fresnel lenses have provided innovative solutions in optical imaging technologies, paving the way for novel applications across various technical domains. Due to their transparent nature, Fresnel lenses enable light to be focused at the rear side without any physical obstruction, distinguishing them from reflective dish systems. This feature eliminates the shading effect of front-mounted equipment, which is particularly advantageous in systems such as Stirling engines that require unobstructed exposure to sunlight. The predominance of plastic in their construction results in significant weight reduction compared to glass lenses and offers greater flexibility in mechanical design and ease of assembly. Their lightweight structure minimizes the energy consumption of dual-axis tracking mechanisms, thereby contributing to higher overall system efficiency. Fresnel lenses, by focusing direct sunlight, can outperform dish-Stirling systems in some respects, as reflective losses are minimized.

Furthermore, their low weight enables highly modular designs, enhancing maneuverability and reducing the mechanical load on tracking motors. Fresnel lenses can be manufactured as a single unit or as large-scale optical assemblies composed of multiple segments. The diameter and total surface area of these lenses can be readily scaled according to the desired degree of solar concentration and target energy output. Large-diameter Fresnel lenses can achieve high focal temperatures, which are useful for both heating applications and for the generation of thermal energy to produce electricity. Despite advantages such as low cost, lightweight construction, and modularity, Fresnel lens-based collectors also present certain limitations in CSP applications. Owing to their plastic composition, they generally exhibit lower resistance to high temperatures. Over extended periods of use, this can result in deformation, reduced optical transmittance, and yellowing. Additionally, environmental factors may cause focal point drift, leading to uneven heat distribution and decreased thermal efficiency. High temperatures achieved with large-diameter lenses also pose safety risks, necessitating specific technical and structural safety measures for use in large-scale CSP installations.

7. DISCUSSION

Concentrated solar power (CSP) plants represent an alternative technology that enables electricity generation by focusing solar radiation onto a specific focal point using mirrors. The overall efficiency of these systems is closely linked to the degree of solar concentration achieved by the mirrors and the effectiveness with which the concentrated energy is transferred to the working fluid at the receiver. Compared to photovoltaic systems, CSP technologies stand out due to their higher efficiency and inherent thermal energy storage capabilities. CSP encompasses a variety of system types tailored to different application needs, offering a broad spectrum of use cases. Each technological configuration offers specific advantages based on its technical characteristics, while also presenting certain structural or operational limitations. Therefore, the selection of an appropriate plant technology must be carefully assessed according to site-specific conditions. Geographical factors and design optimization significantly influence system efficiency.

For instance, tower systems may be more advantageous in regions with high solar irradiance and elevated ambient temperatures. Since the energy output is directly dependent on the efficiency of the technology employed, the conditions under which thermal energy is converted into electricity are of critical importance. The conventional saturated steam Rankine cycle can achieve a net efficiency of approximately 41–43% at a molten salt outlet temperature of 565 °C. Advanced particle receivers operating above 700 °C enable a transition to transcritical or supercritical carbon dioxide (sCO_2) Brayton cycles, where sCO_2 refers to CO_2 in a state above its critical temperature (31.1 °C) and pressure (73.8 bar), exhibiting properties between those of a liquid and a gas. The Brayton cycle itself is a thermodynamic process in which a working fluid is compressed, heated, expanded through a turbine to generate work, and then cooled before repeating the cycle. In the case of sCO_2-based Brayton cycles, reported cycle efficiencies range between 48–52% in the literature [77-80]. Among CSP technologies, STPs stand out due to their large-scale production capacity and extensive deployment potential. The precise alignment and control of the heliostat field is of critical importance for this technology. Recently, the introduction of molten salts as heat transfer and storage media has significantly enhanced system efficiency. One of the key advantages of tower-type CSP systems is the shorter fluid transfer distance compared to parabolic trough or linear Fresnel collectors, which considerably reduces convective energy losses.

With the integration of artificial intelligence-based solar tracking and smart control systems, the efficiency of these plants has seen notable improvements. **Table 2** summarizes the principal characteristics of the four major CSP technologies tower, parabolic trough, dish-Stirling, and Fresnel systems comparing them in terms of operating principles, heat transfer fluids, technical limitations, environmental concerns, and representative large-scale implementations. This comparative overview supports the evaluation of technology suitability under different climatic, geographical, and application-specific conditions.

Table 2. Comparison of the main types of concentrated solar power (CSP) technologies tower, parabolic trough, dish-Stirling, and Fresnel based on operating principles, technical limitations, heat transfer fluids, environmental risks, and large-scale applications.

Criterion/ System	**Tower Type (SPT)**	**Parabolic Trough (PTC)**	**Dish-Stirling**	**Fresnel (LFR)**
Operating Principle	Central tower, multi-heliostat field	Linear focus with parabolic mirrors	Point focus with parabolic dish and Stirling engine	Flat/slightly curved mirrors with linear focus, fixed top tube
Limitations	High investment, salt freezing, water need	Temp. limit, pipe losses	High cost, limited commercial deployment	Temp. limitation, optical loss
Heat Transfer Fluid (HTF)	Molten salt, air, water	Thermal oil, water, nanofluid	Helium, hydrogen, air (Stirling literature)	Water, air, sometimes oil
Environmental Risk	Salt leakage, land use, bird impact	Oil leakage, land use	High temperature risks	Optical losses, mirror soiling
Large-scale Examples	Ivanpah [81]	Andasol [82]	Eurodish[83]	Puerto Errado [84]

In contrast, the primary advantage of parabolic trough and Fresnel-based CSP systems lies in their high modularity and ease of deployment. These systems can be easily modeled for specific locations and constructed in a segmented manner, which often results in significantly lower installation costs compared to power tower systems. Furthermore, as the heat transfer fluid is located closer to the mirrors, more effective thermal focus can be achieved.

However, a fundamental limitation of these systems is the difficulty of integrating large-scale plant infrastructure. Since the heat transfer fluid must circulate throughout the entire pipe network, heat losses occurring along the extended flow path can negatively affect the system's overall efficiency. Additionally, the maximum temperatures achievable in these systems are generally lower than those in dish-Stirling configurations, resulting in decreased thermodynamic cycle efficiency and increased energy conversion losses. Although thermal energy storage is theoretically possible in linear Fresnel systems, commercial-scale implementations remain limited. This is primarily because such systems are originally designed for direct steam generation. As a result, when energy storage is required, either steam accumulators must be employed or the Fresnel collector field must be integrated with high-temperature storage media such as molten salts. Technically, such hybrid systems are feasible and have been tested in some pilot-scale projects. Among all solar-based electricity generation methods, dish-Stirling systems offer one of the highest thermodynamic efficiencies due to their strong optical concentration capability. In these systems, the Stirling engine an external combustion engine operating on a closed cycle with gases such as air, hydrogen, or helium is driven by the thermal expansion of the working fluid caused by concentrated sunlight. These engines are known for their high operational efficiency.

Solar radiation focused by a large parabolic dish onto a receiver heats the working gas (e.g., air, hydrogen, or helium), which in turn drives the Stirling engine to produce mechanical work. The Stirling engines positioned at the focal point of parabolic dish reflectors can reach temperatures exceeding 1000 °C. At such elevated temperatures, the working gas typically air expands significantly, driving the pistons and enabling mechanical power generation, which is subsequently converted into electricity via a generator. The combination of extremely high focal point temperatures with Stirling engines results in a significantly higher power generation capacity compared to other CSP technologies.

Dish-Stirling systems have been reported to achieve solar-to-electric conversion efficiencies of up to 30%, making them one of the most efficient solar thermal power generation methods available [85]. Dish-Stirling systems do not inherently incorporate integrated thermal energy storage infrastructure due to their design, which emphasizes the independent operation of each dish and direct mechanical energy conversion. In theory, compact thermal storage modules utilizing phase change materials (PCMs) could be integrated at the focal point of each unit, or the generated electrical energy could be stored in batteries.

However, such solutions are not widely implemented in practice, as they may increase system costs and reduce overall efficiency. Consequently, Dish-Stirling configurations provide electricity only during periods of direct solar irradiation and cannot supply power to the grid at night unless supplemented by an external energy storage unit. Unlike photovoltaic systems, concentrated solar power (CSP) plants cannot be effectively deployed in all geographic regions. The performance of CSP technologies is directly dependent on the intensity of direct normal irradiance (DNI); hence, their efficiency significantly drops under cloudy or shaded conditions. For this reason, regions with high annual solar insolation, particularly arid and semi-arid desert climates, are preferred for CSP deployment. Additionally, CSP plants require substantial land area. Tower systems, parabolic troughs, and linear Fresnel systems typically involve expansive heliostat fields or mirror arrays that can span hundreds of hectares. Beyond energy generation efficiency, sustainability considerations are becoming increasingly important. Strategies such as the use of environmentally benign and recyclable materials, integration of energy recovery systems, and reuse of waste heat in auxiliary processes are gaining attention. However, major barriers to the widespread adoption of CSP technologies include high capital investment, complex maintenance requirements, extensive land use, and environmental concerns such as the intense solar flux potentially harming avian populations near focal zones. Due to the concentration of sunlight, focal point temperatures in CSP systems can reach up to 1500 °C. The extremely high energy density can be lethal to bird flocks flying through the area. Water use constitutes another environmental impact of CSP. Traditional steam-turbine-based CSP plants require significant amounts of water for steam generation and cooling processes. In water-scarce desert regions, wet cooling is not considered sustainable.

Alternatives such as dry cooling technologies or air-cooled Stirling engines can reduce water consumption, though they may slightly reduce efficiency. Furthermore, mirror cleaning requires periodic water use. In terms of water use, tower and trough plants have comparable demands. Dish-Stirling systems, on the other hand, are typically air-cooled and do not consume water for energy generation, making them the CSP technology with the lowest water footprint. From an environmental safety perspective, the nature of the heat transfer fluid (HTF) is also critical. Parabolic trough and some Fresnel systems use synthetic thermal oils that are flammable and toxic. In the event of leaks or pipeline ruptures, these fluids can pose environmental hazards, requiring robust containment and monitoring systems.

In contrast, molten salts used in tower systems are relatively benign; however, if spilled and solidified, they can cover soil surfaces or contaminate water resources, necessitating careful storage and maintenance protocols. The economic feasibility of CSP projects depends not only on their technological advantages but also heavily on their capital and operational costs. In general, parabolic dish systems are considered the most expensive, while linear Fresnel systems are the least costly among CSP technologies. In Dish-Stirling systems, each unit is equipped with an independent Stirling engine and generator. The presence of high-precision mechanical components and the limited scalability of industrial mass production significantly increase the unit installation cost of this technology. In contrast, linear Fresnel systems are based on flat, simple mirror structures that reduce material consumption and manufacturing complexity, thereby lowering total initial capital investment. Parabolic trough systems still require substantial capital investment due to components such as curved mirrors, vacuum-insulated receiver tubes, and oil-based heat exchangers. Tower systems demand massive central infrastructures (e.g., tall towers, high-temperature receivers, molten salt tanks) and thousands of heliostats.

While the upfront cost is high, the levelized cost per unit of energy may decrease with large-scale deployment. The construction and commissioning of CSP plants involve multi-stage technical procedures requiring high structural precision and intensive labor. Environmental and structural factors such as wind loads, dust accumulation, and mechanical failures are of critical concern. Parabolic trough collector (PTC) systems require specific installation dynamics: the construction of collector loops and the precise alignment of receiver tubes to the mirror arrays are crucial for achieving optimal optical efficiency, necessitating extensive labor and coordination. One of the key factors affecting overall system performance is the correct slope and optical focus of collector loops. Detailed optical alignment, expansion joints, pump stations, and heat transfer fluid systems must therefore be carefully integrated. In large-scale systems, pressure drops and heat losses during fluid circulation significantly affect thermal efficiency. Although Fresnel system installations are mechanically simpler due to the planar nature of mirrors, they require the precise angular positioning of numerous flat mirror panels and structural support for a long, shared receiver tube. The lower profile of Fresnel systems reduces wind loads and improves structural stability. Dish-Stirling systems are relatively easy to install on a unit basis, but a plant-scale implementation involves the deployment and commissioning of hundreds or thousands of individual units. Since each dish has its own solar tracking system and engine-generator set, mass deployment and maintenance coordination are challenging.

The high temperatures generated by CSP systems are valuable not only for electricity generation but also for direct industrial process heat. Sectors such as food processing, textiles, chemicals, mining, and paper manufacturing operate with thermal processes requiring temperatures in the range of 150–500 °C. In this context, CSP technologies are emerging as environmentally friendly and sustainable alternatives to fossil fuel-based heat sources. Parabolic trough and linear Fresnel collectors, with the ability to generate temperatures up to 500 °C, have reached the technical maturity necessary for integration into industrial thermal applications, offering reliable solutions for industrial heat demands. To enhance future CSP performance, the development of new heat transfer fluids that are high-temperature-resistant, cost-effective, and environmentally benign is of critical importance. In particular, materials capable of withstanding temperatures above 800 °C and resisting corrosion require further field-tested evaluation representing a significant gap in the current literature.

Technological trends expected to gain traction in the coming years include particle-based receivers and supercritical CO_2 cycles, both aimed at improving system efficiency. Moreover, artificial intelligence-assisted heliostat control systems have the potential to enhance optical performance through optimized solar tracking. In this context, CSP systems could evolve into next-generation power plants capable of delivering baseload energy, equipped with high-capacity integrated storage solutions. However, large-scale deployment will require more comprehensive technical and economic analyses. Minimizing environmental impacts, maximizing resource efficiency, and designing systems tailored to local conditions will be key determinants of success. The widespread adoption of CSP technologies will depend on innovative engineering solutions and the implementation of supportive policy frameworks. In conclusion, CSP systems are poised to play a pivotal role in building a future energy landscape free from fossil fuels.

8. CONCLUSIONS

This review has comprehensively examined the current state, thermodynamic performance, and thermal energy storage capabilities of key Concentrated Solar Power (CSP) technologies, including central receiver (SPT), parabolic trough (PTC), dish-Stirling, and linear Fresnel reflector (LFR) systems. The findings indicate that CSP offers not only the capability to convert direct solar irradiance into high-temperature thermal energy, but also the ability to dispatch power on demand through advanced thermal storage systems. A common trend observed across all CSP plant types is the increasing utilization of heat transfer fluids (HTFs) that exhibit chemical and thermal stability at elevated temperatures such as molten salt mixtures, supercritical CO_2, and nanofluids. Concurrently, there is significant progress in developing absorber materials with low radiative losses and superior thermal performance, including ceramic-metal composites and advanced selective coatings. Furthermore, CSP systems are advancing toward the integration of thermodynamic cycles that promise higher efficiencies, such as supercritical Brayton and hybrid Rankine–Brayton cycles. These developments are narrowing the efficiency gap between CSP and photovoltaic-battery hybrid systems, positioning CSP as a viable competitor in large-scale renewable energy production. In conclusion, CSP technologies are not merely transitional solutions but are strong candidates to become foundational components of future energy infrastructures, particularly at the intersection of industrial applications, grid integration, and environmental sustainability.

DECLARATION OF ETHICAL STANDARDS

The authors declare that this study does not require ethics committee approval or special permissions.

CONTRIBUTION OF THE AUTHORS

Olcay Kaan Çakır: Conceived the study concept, conducted the literature review, and wrote the manuscript.

Mesut Ekmekçi: Contributed to literature analysis

Şule Erten Ela: Supervised the study and provided critical revisions to the final version of the manuscript

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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