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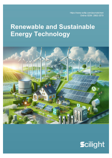

Review

Solar Thermal Technologies towards Sustainability

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Abstract: Solar thermal energy represents a mature and versatile pathway for harvesting solar radiation in the form of useful heat across a wide range of temperature levels. Unlike photovoltaic-based technologies, solar thermal systems directly address thermal energy demands in residential, industrial, and power-generation sectors, which constitute a substantial share of global energy consumption. This review presents a structured overview of solar thermal technologies and their practical applications using a temperature-oriented perspective rather than a conventional collector-based classification. Solar thermal systems are categorized according to their delivered heat quality, spanning low-, medium-, and high-temperature regimes, and the functional role of different collector concepts within each regime is discussed. The review further maps these temperature ranges to key application domains, including domestic heat supply, industrial process heat, solar-driven desalination, cooling technologies, and concentrated solar power systems. In addition, critical design and integration aspects such as thermal losses, heat transfer fluids, storage compatibility, and system-level challenges are examined. By reorganizing existing knowledge around heat demand and operating temperature, this review aims to provide clear guidance for researchers, engineers, and practitioners seeking to select and integrate appropriate solar thermal solutions for specific applications.

Keywords: solar thermal energy; thermal collectors; heat quality; industrial process heat; thermal energy storage

1. Introduction

The increasing global demand for energy has risen by approximately 50% over the past three decades, coupled with environmental concerns and the need to decarbonize heat-intensive sectors, and is projected to continue growing through 2050. This has renewed interest in solar thermal energy (STE) as a reliable and sustainable technology [1]. Unlike solar technologies that primarily target electricity generation, solar thermal systems directly convert solar radiation into useful heat, addressing a substantial portion of energy consumption associated with domestic heating, industrial processes, water treatment, and power generation [2]. Heat demand represents a dominant share of final energy use worldwide (~50% of total final energy consumption), making solar thermal technologies particularly relevant for achieving long-term sustainability goals.

STE systems operate by collecting incident solar radiation and transferring the absorbed energy to a working fluid, which can then be utilized immediately or stored for later use, with thermal efficiencies ranging from 30% to over 70%, where the usefulness of the collected thermal energy is strongly dependent on its operating temperature level, often referred to as heat quality, and system design. Low-temperature thermal energy is typically sufficient for residential and building-related applications, whereas medium- and high-temperature heat is required for industrial processes, cooling technologies, and electricity generation. Consequently, the operating temperature range of a solar thermal system plays a decisive role in determining its suitability for a given application.

Existing literature commonly reviews solar thermal technologies by categorizing collector designs based on their geometry or concentration mechanism. While this approach provides valuable technical insight, it may obscure the practical relationship between heat demand and system selection. In real-world applications, the primary question faced by engineers and decision-makers is not the collector type itself, but whether the system can reliably deliver thermal energy at the required temperature level with acceptable efficiency, cost, and operational complexity.

In this context, the present review adopts a temperature-oriented perspective to organize and assess solar thermal technologies and their applications. Rather than focusing on individual collector configurations in isolation, solar thermal systems are classified according to the quality of thermal energy they deliver, spanning low-, medium-, and high-temperature regimes. The functional role of different collector concepts within these regimes is discussed, emphasizing their performance characteristics and integration potential rather than their structural details alone. Furthermore, this review maps the identified temperature ranges to major application domains, including domestic heat supply, industrial process heat, solar-driven desalination, cooling and refrigeration systems, and concentrated solar power (CSP) generation. Key design and integration considerations, such as thermal losses, heat transfer fluid (HTF) selection, storage compatibility, and system-level challenges, are also examined to provide a holistic understanding of solar thermal system deployment.

2. Classification of Solar Thermal Systems Based on Heat Output

The performance and applicability of a solar thermal system are primarily determined by the temperature level of the thermal energy it can deliver. This temperature level governs not only the range of feasible applications but also system complexity, efficiency, and cost. For this reason, solar thermal technologies are classified in this review according to their useful heat output into low-, medium-, and high-temperature systems. This classification provides a practical framework for matching solar thermal solutions to specific thermal demands.

2.1. Low-Temperature Solar Thermal Systems (<100 °C)

Low-temperature solar thermal systems are designed to supply heat at temperatures typically below 100 °C. These systems are widely used in residential and commercial applications where the thermal demand does not require high-grade heat. Common uses include domestic hot water production, space heating, swimming pool heating, and preheating for various low-temperature processes [3].

At these temperature levels, the dominant design objective is to maximize heat collection while minimizing thermal losses to the surrounding environment. Since the temperature difference between the absorber surface and ambient air is relatively small, radiative and convective losses can be controlled effectively without the need for optical concentration. As a result, low-temperature systems generally rely on non-concentrating collector concepts that are capable of harvesting both direct and diffuse solar radiation.

The simplicity of low-temperature solar thermal systems contributes to their widespread adoption. They typically operate with fixed collector orientations, do not require tracking mechanisms, and use water or water-based fluids as heat transfer media. Their relatively low operating pressures and temperatures also enhance system reliability and reduce maintenance requirements. However, their limited temperature output restricts their applicability to processes with modest thermal requirements.

2.2. Medium-Temperature Solar Thermal Systems (100–400 °C)

Medium-temperature solar thermal systems operate in the range of approximately 100 to 400 °C and represent a transition zone between building-scale applications and high-temperature power generation. This temperature range is particularly relevant for industrial process heat, solar-driven cooling systems, and certain thermal treatment processes [4].

As operating temperatures increase, thermal losses become more pronounced, necessitating improved system designs to maintain acceptable efficiency. Moderate optical concentration is often employed in this temperature regime to increase the incident solar flux on the absorber surface while reducing the effective heat loss area. In addition, selective absorber coatings and enhanced insulation techniques are commonly used to limit radiative and convective losses.

Medium-temperature systems often require some form of solar tracking to maintain effective concentration throughout the day, which increases system complexity compared to low-temperature installations. HTFs used in this regime may include pressurized water, thermal oils, or other engineered fluids capable of maintaining stability at elevated temperatures. These systems offer greater flexibility than low-temperature technologies but demand more careful design, control, and integration, particularly when coupled with thermal storage or industrial processes operating under variable load conditions.

2.3. High-Temperature Solar Thermal Systems (>400 °C)

High-temperature solar thermal systems are designed to deliver thermal energy at temperatures exceeding 400 °C, enabling applications such as electricity generation, high-temperature industrial processing, and advanced thermochemical cycles. At these temperatures, the quality of thermal energy is sufficient to drive conventional heat engines and achieve meaningful thermal-to-electric conversion efficiencies [5].

Achieving such high operating temperatures requires a strong optical concentration of solar radiation. High-temperature systems typically utilize point- or line-focus configurations combined with precise solar tracking to concentrate direct normal irradiance onto a relatively small receiver area. This approach significantly increases the solar flux density, allowing very high absorber temperatures while minimizing relative heat losses.

The technical complexity of high-temperature solar thermal systems is considerably greater than that of lower-temperature technologies. Receiver design, material selection, and thermal stress management become critical challenges, particularly under fluctuating solar conditions. HTFs in this regime include molten salts, pressurized gases, or steam, each with specific advantages and operational constraints. Despite their complexity and higher capital costs, high-temperature solar thermal systems offer unique advantages, particularly when integrated with thermal energy storage (TES), enabling a dispatchable and controllable energy supply.

3. Functional Overview of Solar Thermal Collectors

The temperature regimes defined in Section 2 directly determine which collector concepts are technically viable. This section examines how collector design choices are driven by these temperature requirements. Solar thermal collectors serve as the interface between incident solar radiation and the thermal energy delivered to the working fluid. Rather than treating collectors as isolated technologies, this review considers them according to their functional role in enabling specific temperature ranges. Collector design choices, such as optical configuration, absorber construction, and tracking requirements, are primarily driven by the level of heat that must be supplied to the target application [6].

3.1. Non-Concentrating Collectors for Low-Grade Heat

Non-concentrating collectors capture solar energy directly without focusing sunlight. Their main objective is to maximize absorbed radiation over a large surface area while minimizing heat losses, making them suitable for low-temperature applications where modest thermal energy is needed and diffuse solar radiation is significant.

The most common examples are flat-plate collectors and evacuated tube collectors, shown in Figure 1 and Figure 2, respectively. Flat-plate collectors feature a flat absorber plate with a transparent cover to reduce convective losses [7], while evacuated tube collectors use vacuum-sealed tubes to minimize heat loss [8], allowing slightly higher operating temperatures than flat-plate designs. Both types operate efficiently without tracking systems, offering mechanical simplicity, ease of installation, and reliable long-term performance. Flat plate collectors typically achieve thermal efficiencies around 50–65% under favorable conditions, while evacuated tube collectors can exceed 70% due to reduced convective losses. These collectors are widely deployed, with over 50 million m^2 installed capacity worldwide, primarily for residential domestic hot water and space heating.

However, their main limitation is their reduced efficiency at higher temperatures. As the absorber temperature rises, radiative and convective losses increase, limiting their ability to provide heat above roughly the boiling point of water (or slightly higher under pressurized conditions).

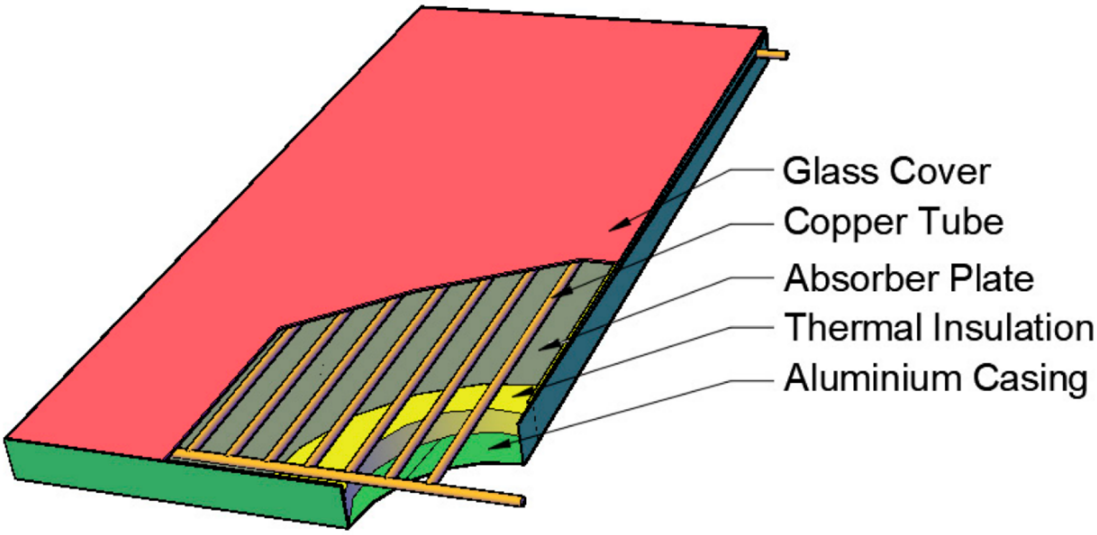

Figure 1. Structure of a solar flat-plate collector [9].

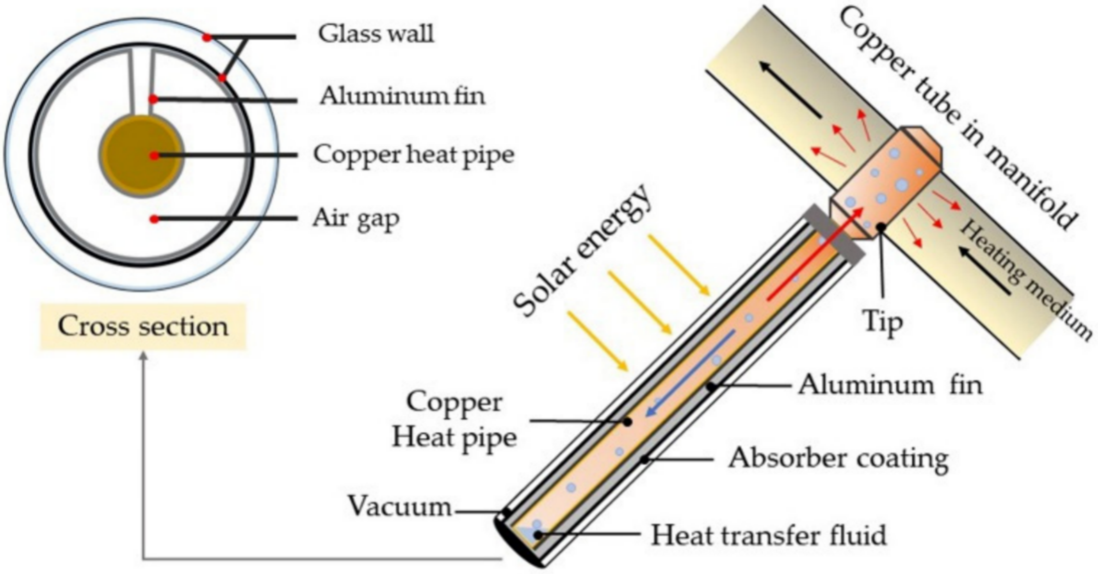

Figure 2. Schematic diagram of an evacuated tube collector [10].

3.2. Moderately Concentrating Collectors for Intermediate Temperatures

Moderately concentrating collectors increase the solar flux on the absorber by using optical concentration, bridging the gap between low- and high-temperature systems. This allows them to deliver medium-grade thermal energy suitable for industrial processes, solar cooling, and medium-temperature heating applications.

Common types in this category include parabolic trough collectors and linear Fresnel collectors, shown in Figure 3 and Figure 4, respectively. Parabolic troughs use curved reflectors to focus sunlight along a receiver tube [11], while linear Fresnel systems employ multiple flat mirrors to concentrate light onto a linear absorber [12]. Partial solar tracking is typically required, but tracking precision is less stringent than in high-concentration systems. These collectors commonly achieve operating temperatures in the range of 100–400 °C. Parabolic trough fields, for instance, have been proven in CSP plants with annual capacity factors between 20% and 40% without storage.

Performance depends on optical efficiency, absorber design, and heat removal effectiveness. Proper selection of HTFs and integration with thermal storage also significantly affects both efficiency and economic feasibility.

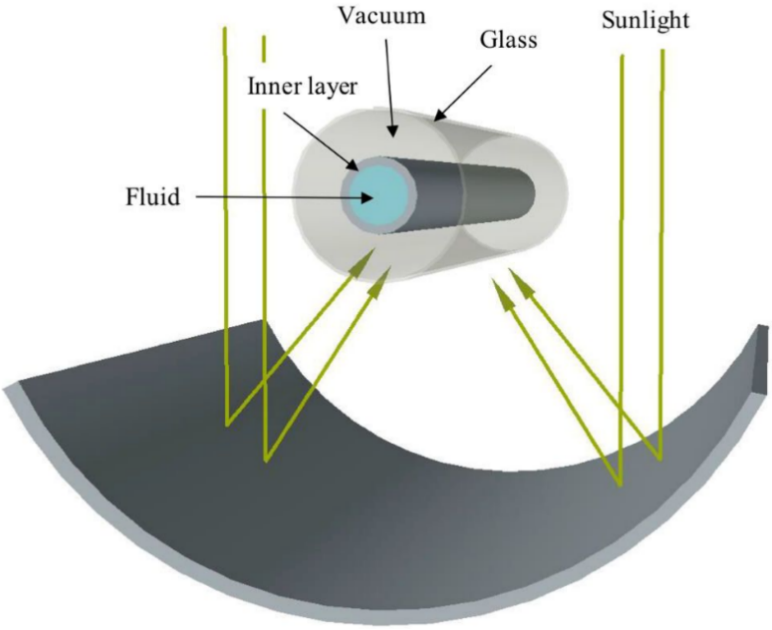

Figure 3. Schematic diagram of a parabolic trough solar collector [13].

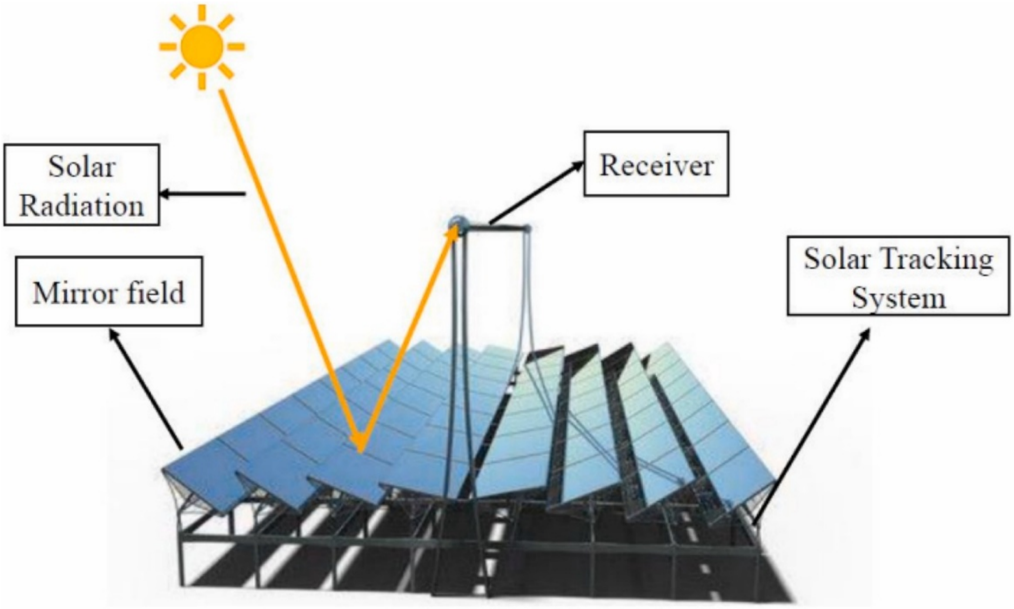

Figure 4. Linear Fresnel solar collector [14].

3.3. High-Concentration Collectors for High-Quality Heat

High-concentration collectors are designed to deliver high-grade thermal energy at temperatures above several hundred degrees Celsius, suitable for electricity generation and high-temperature industrial processes. Strong optical concentration is required to achieve very high solar flux densities at the receiver (>1000 kW/m^2). Advanced CSP plants can incorporate TES with storage capacities exceeding 10 h of full load equivalent.

Examples include parabolic dish collectors and central receiver (heliostat) tower systems, shown in Figure 5 and Figure 6, respectively. Parabolic dishes focus sunlight onto a single point [15], while central receiver systems use arrays of heliostats to concentrate sunlight onto a tower-mounted receiver [16]. These systems demand precise solar tracking and operate optimally under direct, high-intensity sunlight.

High operating temperatures impose strict requirements on receiver materials, thermal stability, and structural integrity. Although technically complex, these collectors can achieve high thermal efficiency. When combined with TES, they provide controllable and dispatchable energy, giving solar thermal systems a unique advantage among renewable energy technologies.

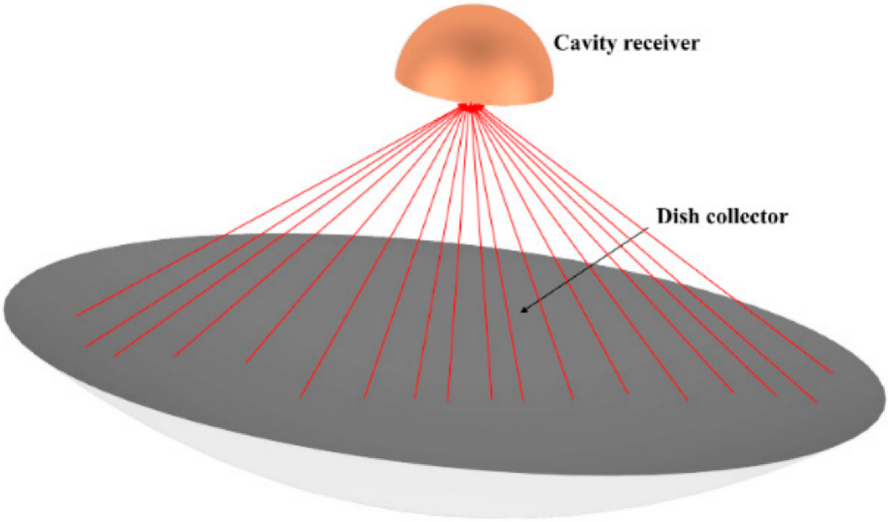

Figure 5. Parabolic dish solar collector [17].

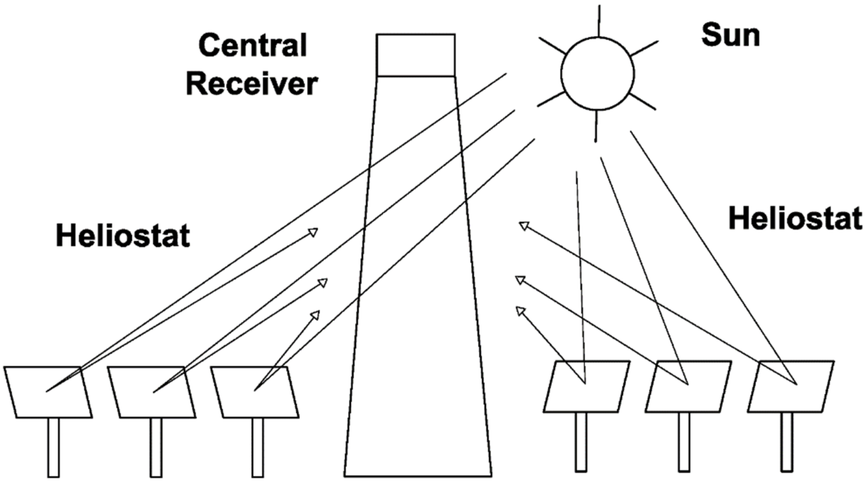

Figure 6. Central receiver solar collector [18].

4. Solar Thermal Energy Applications

Building on the temperature classifications of Section 2 and the collector capabilities outlined in Section 3, this section maps these findings to specific application domains, showing how thermal demand requirements align with the appropriate collector type and operating temperature range. Real-world performance of solar thermal systems varies considerably across geographic and climatic conditions. Low-temperature collectors in high-irradiance regions such as the Middle East and North Africa typically achieve higher annual yields than those deployed in temperate climates, where diffuse radiation dominates. Similarly, medium-temperature systems supplying industrial process heat have demonstrated solar fraction rates ranging from 20% to 60% depending on process temperature, load profile, and site irradiance. These variations underline the importance of matching collector type and system design to both the thermal demand and the local solar resource. The practical value of STE lies in its ability to meet diverse heat demands across multiple sectors. Each application imposes specific requirements in terms of temperature level, reliability, and system integration. By linking applications directly to heat quality and collector functionality, solar thermal technologies can be more effectively matched to real-world energy needs.

4.1. Domestic and Building Heat Supply

One of the most established applications of STE is the provision of heat for residential and commercial buildings. Typical uses include domestic hot water production, space heating, and combined heat supply for multifamily or institutional buildings [19,20]. These applications generally require low-temperature heat, making them well suited to non-concentrating solar thermal systems.

In building-scale installations, the temporal mismatch between solar availability and heat demand is a central challenge. Peak solar input often occurs during daytime hours, while heat demand may extend into the evening or early morning. As a result, TES plays a crucial role in enhancing system usability and increasing solar contribution levels [21]. The relatively low operating temperatures involved allow for cost-effective storage solutions and straightforward system control.

From an integration perspective, solar thermal systems for buildings are often combined with conventional heating technologies to ensure reliability during periods of low solar availability. The simplicity and proven performance of low-temperature solar thermal systems have contributed to their widespread adoption in both new constructions and retrofit projects.

4.2. Industrial Process Heat

Industrial activities account for a 30% of global energy use, with a significant fraction below 400 °C, which can be partially or fully supplied by STE. Depending on the specific process, heat requirements may range from low-temperature washing and drying to medium-temperature heating, distillation, and chemical treatment [22].

Solar thermal systems operating in the medium-temperature range are particularly relevant for industrial process heat applications. These systems must be carefully designed to integrate with existing production lines, which often require a continuous and reliable heat supply. Variability in solar input introduces challenges related to process stability, making system control and thermal storage essential components of successful industrial integration.

The feasibility of solar thermal process heat depends not only on temperature compatibility but also on spatial constraints, operational schedules, and economic considerations. While high-temperature industrial processes may exceed the practical limits of many solar thermal technologies, a substantial portion of industrial heat demand falls within temperature ranges that are well aligned with current solar thermal capabilities. Real-world deployments confirm this compatibility. In Mexico, several dairy plants use parallel trough collectors for pasteurization at 60–95 °C, demonstrating successful solar heat integration into continuous industrial production lines [23].

4.3. Solar Thermal Desalination

Water scarcity in many regions has driven interest in desalination technologies powered by renewable energy sources. STE offers a direct and efficient means of supplying the heat required for thermally driven desalination processes [24,25]. These processes typically operate at low to medium temperature levels (50–120 °C), making them compatible with a range of solar thermal system configurations.

In solar thermal desalination systems, the matching of collector output to process requirements is critical for achieving stable and efficient operation. The integration of thermal storage can further enhance system performance by smoothing fluctuations in solar input and enabling extended operating periods. Solar thermal desalination is particularly attractive in arid and remote regions where solar resources are abundant and conventional energy infrastructure may be limited.

4.4. Solar-Driven Cooling and Refrigeration

STE can also be utilized to drive cooling and refrigeration systems through heat-activated cycles [26]. These applications convert thermal energy into cooling capacity, offering an alternative to electrically driven cooling technologies, especially in regions with high cooling demand coinciding with strong solar availability.

Heat-driven cooling systems typically require medium-temperature heat to operate effectively. This requirement necessitates the use of solar thermal collectors capable of delivering sufficiently high and stable temperatures. System performance is influenced by factors such as heat input quality, cycle efficiency, and integration with auxiliary components. Although solar-driven cooling systems are generally more complex than conventional cooling technologies, they offer the potential to reduce electrical peak loads and improve overall energy system resilience.

4.5. Solar Thermal Power Generation

Solar thermal power generation represents the highest-temperature application of solar thermal technology [27]. By converting high-quality thermal energy into electricity, these systems extend the role of solar thermal beyond direct heat supply. High-temperature solar thermal systems rely on strong optical concentration to achieve the temperatures required for efficient power cycles.

A distinguishing feature of solar thermal power generation is the ability to incorporate large-scale TES. This capability allows electricity production to be decoupled from instantaneous solar availability, enabling dispatchable operation and improved grid integration. While such systems involve significant technical complexity and capital investment, they offer a unique pathway for renewable electricity generation with enhanced controllability.

4.6. Emerging and Advanced Applications

Solar thermal technologies are increasingly deployed in advanced energy-conversion pathways that exploit the unique ability of concentrating systems to deliver high-temperature, dispatchable heat. The most extensively studied of these pathways is solar thermochemical fuel production. By driving two-step redox cycles (e.g., based on ceria, perovskites, or ferrite materials) at receiver temperatures of 1400–1500 °C, concentrated solar radiation can split water and CO_2 to produce hydrogen and synthesis gas, offering a route to carbon-neutral fuels with theoretical solar-to-fuel efficiencies exceeding 20% [28].

A closely related application is solar-driven CO_2 reduction and methane reforming. Solar reactors operating in the 800–1000 °C range have been used to perform steam–methane reforming, dry reforming, and direct CO_2 splitting, producing high-value syngas with reduced fossil fuel consumption [29]. Pilot demonstrations such as the SOLREF project has validated these concepts at scales up to several hundred kilowatts of solar input.

At the highest temperature regime, advanced industrial applications include solar metallurgy (e.g., zinc and aluminum production, lime calcination, and cement clinker manufacture). These processes traditionally rely on fossil-fuel combustion at temperatures above 1000 °C and represent a significant fraction of global industrial CO_2 emissions; replacing combustion heat with concentrated solar heat offers a direct decarbonization pathway.

5. Design and Integration Considerations

A central challenge for all solar thermal technologies is the intrinsic variability of the solar resource. Diurnal cycles, seasonal swings in irradiance, and short-term cloud transients impose unsteady boundary conditions on the receiver, which translate into fluctuating outlet temperatures and thermal stresses in the absorber, piping, and heat-transfer fluid. In high-concentration line- and point-focus systems, sudden cloud passages can cause defocus events with rapid temperature drops, accelerating fatigue of receiver tubes and selective coatings. At the application level, intermittency reduces the achievable solar fraction, complicates the integration of solar heat into industrial processes that require steady set-points, and erodes the effective capacity factor of CSP plants. Three complementary mitigation strategies are routinely deployed. First, thermal energy storage (sensible, latent, or thermochemical) decouples thermal supply from instantaneous solar input and is widely used in modern CSP plants to provide 6–15 h of dispatch. Second, hybridization with auxiliary heat sources—natural-gas or biomass boilers, waste heat, or electric resistive elements powered by surplus renewable electricity—guarantees process stability during prolonged cloudy periods. Third, advanced direct normal irradiance (DNI) forecasting and model-predictive control allow plant operators to anticipate cloud events and adjust dispatch and defocus strategies, smoothing thermal output and improving plant lifetime

The successful deployment of solar thermal systems depends not only on collector performance but also on how effectively the system is designed and integrated within its intended application. Across all temperature regimes, a number of cross-cutting factors influence efficiency, reliability, and economic viability. These considerations become increasingly important as operating temperatures rise and system complexity increases.

5.1. Optical and Thermal Performance Trade-Offs

Solar thermal system performance is governed by a balance between optical gains and thermal losses. Optical efficiency determines how much of the incident solar radiation is captured by the collector, while thermal efficiency reflects how effectively the absorbed energy is retained and transferred to the working fluid. At low operating temperatures, thermal losses are relatively modest, allowing simple collector designs to achieve high efficiencies. As temperature increases, radiative and convective losses grow significantly, necessitating improved optical concentration and enhanced insulation.

Design choices that increase optical concentration can raise operating temperatures but often introduce additional losses due to imperfect reflectivity, alignment errors, or shading. Consequently, the optimal system configuration depends on carefully matching the degree of concentration to the required heat quality, rather than maximizing temperature indiscriminately. This trade-off is particularly relevant in medium-temperature applications, where modest increases in temperature can yield substantial gains in applicability without excessive complexity.

The optical performance of a solar thermal collector is largely governed by the spectral properties of its absorber surface. Two design philosophies dominate. Non-selective absorbers, typically realized with black paints or oxidized metallic surfaces, exhibit a high solar absorptance ($\alpha \approx 0.90$–0.97) but also a high thermal emittance in the infrared ($\varepsilon \approx 0.85$–0.95). They are inexpensive, robust, and adequate for low-temperature applications such as swimming-pool heating and unglazed flat-plate collectors, where the absorber operates close to ambient temperature and infrared re-emission losses remain modest.

For medium- and high-temperature collectors, the absorber temperature is significantly above ambient, and radiative losses become the dominant performance penalty. Spectrally selective absorbers—typically multilayer cermet or nanostructured coatings—are designed to maximize solar absorptance wavelength range while minimizing thermal emittance, thereby suppressing re-radiation. Recent work has further improved selectivity, thermal stability, and air-stability through engineered nanostructures and refractory metal multilayers [30,31]. The choice of absorber coating, therefore, tracks closely with the temperature regimes of Section 2: non-selective surfaces are sufficient below 100 °C; selective coatings become essential above ~150 °C; and ultra-stable, refractory selective coatings are required above 400 °C, where coating durability under thermal cycling and oxidative atmospheres dictates plant lifetime.

5.2. Selection of Heat Transfer Fluids

The choice of HTF plays a critical role in determining system performance, safety, and durability [32]. Fluids must be compatible with the operating temperature range, pressure conditions, and material constraints of the system. In low-temperature systems, water and water-based mixtures are commonly used due to their favorable thermal properties, low cost, and ease of handling. As operating temperatures increase, alternative fluids such as thermal oils, molten salts, or gases may be required to maintain stability and avoid degradation. Water is suitable up to around 120 °C, while thermal oils operate effectively up to 300–350 °C. Molten salts and gases are used for higher temperatures; for instance, molten nitrate salts are stable up to ~600 °C.

Each class of HTF introduces specific advantages and limitations. For example, fluids suitable for high-temperature operation may impose stricter requirements on system sealing, material selection, and maintenance. In addition, environmental and safety considerations increasingly influence fluid selection, particularly in large-scale or industrial installations. The choice of fluid must therefore be evaluated in conjunction with overall system design and application requirements.

5.3. Integration of Thermal Energy Storage

Thermal energy storage is a key enabler for improving the usability and flexibility of solar thermal systems [33]. TES integration raises CSP capacity factors by more than 90% compared to plants without storage (22–28%) [34]. By decoupling energy collection from energy use, storage allows solar thermal systems to better match supply with demand and to maintain operation during periods of low solar availability. Storage integration is relevant across all temperature ranges, though the appropriate storage technology varies with operating conditions.

Low-temperature systems often employ sensible heat storage using water or similar media, benefiting from simplicity and low cost. Medium- and high-temperature systems may require more advanced storage concepts to handle higher temperatures and energy densities. The integration of storage introduces additional design considerations, including heat losses, charging and discharging strategies, and control complexity. Nevertheless, effective thermal storage significantly enhances the value proposition of solar thermal systems, particularly in applications requiring continuous or dispatchable heat supply.

5.4. System Control and Operational Challenges

Solar thermal systems operate under inherently variable solar conditions, making system control an essential aspect of reliable performance. Fluctuations in solar irradiance can lead to changes in operating temperature, pressure, and heat output, which must be managed to protect system components and maintain consistent service to the end user.

Control strategies range from simple on–off operation in low-temperature systems to more advanced regulation schemes in high-temperature and industrial applications. The integration of auxiliary energy sources, thermal storage, and variable loads further increases control complexity. Effective system control not only improves performance but also extends component lifetime and enhances overall system safety.

6. Challenges and Future Perspectives

Despite their technical maturity and broad applicability, solar thermal systems continue to face several challenges that influence their adoption and large-scale deployment. One of the primary barriers remains economic competitiveness, particularly in regions where conventional energy prices are low or where policy support mechanisms are limited. Initial investment costs, especially for medium- and high-temperature systems, can be significant due to the need for advanced materials, tracking mechanisms, and thermal storage components.

Beyond operational carbon savings, a comprehensive sustainability assessment of solar thermal systems requires consideration of their full life cycle environmental footprint. Manufacturing of collector components, selective coatings, and heat transfer fluids involves energy-intensive processes and, in some cases, scarce or hazardous materials. End-of-life recycling of glass, aluminum, and selective absorber coatings remains technically challenging and is not yet standardized across the industry. Life cycle assessments of flat-plate and evacuated tube collectors report embodied carbon values, which are significantly lower than fossil fuel alternatives but not negligible. For CSP systems, embodied carbon is higher due to material intensity, though long operational lifetimes and high capacity factors reduce the lifecycle impact considerably.

Economic viability varies considerably across temperature regimes and is a key factor in technology selection. Low-temperature systems such as flat-plate and evacuated tube collectors carry the lowest capital costs and shortest payback periods, making them accessible for residential and small commercial applications. Medium-temperature systems require higher initial investment due to tracking mechanisms and more complex receiver designs, but remain economically viable for industrial process heat applications where conventional fuel costs are significant. High-temperature CSP systems involve the highest capital intensity, driven by heliostat fields, advanced receivers, and thermal storage, though economies of scale and declining component costs have improved their competitiveness in recent years. Decision-makers are directed to the primary sources cited in this review for site-specific levelized cost of heat and capital cost estimates, as these figures are highly sensitive to local solar resources, financing conditions, and system scale.

Land and resource requirements also present challenges for certain applications. High-temperature solar thermal systems typically require large areas with high levels of direct solar radiation, which may restrict deployment to specific geographic regions. In addition, water usage for cooling or cleaning purposes can be a concern, particularly in arid environments where solar resources are otherwise abundant. Addressing these issues requires continued research into system designs that reduce land footprint and water consumption.

From a technical perspective, improving system durability and long-term performance remains a priority. Exposure to high temperatures, thermal cycling, and environmental conditions can lead to material degradation and performance losses over time. Advances in absorber coatings, HTFs, and receiver materials are essential to enhance system reliability and reduce maintenance requirements. Simplifying system architecture without compromising performance is another important research direction, particularly for applications requiring robust and low-maintenance solutions.

Looking forward, STE is expected to play an increasingly important role in decarbonizing heat demand, especially in sectors that are difficult to electrify. Industrial process heat, thermal desalination, and dispatchable power generation represent areas where solar thermal technologies offer unique advantages. Future research is likely to focus on improved integration with TES, hybridization within thermal systems, and optimized control strategies to enhance flexibility and reliability. By aligning technological development with application-specific requirements, solar thermal systems can contribute meaningfully to a more sustainable and resilient energy landscape.

Moreover, the further development of solar thermal technologies will be shaped by progress along five mutually reinforcing fronts. (i) Advanced absorber and receiver materials—including refractory cermet coatings, ceramic-particle receivers, and SiC/oxide composites—will push achievable working temperatures above 800 °C, raising thermodynamic conversion efficiency and enabling supercritical-CO_2 and Brayton-cycle integration. (ii) Next-generation heat-transfer fluids and storage media, such as molten chlorides, liquid metals, and engineered nanofluids, are expected to expand the operating envelope of medium- and high-temperature systems while improving thermal conductivity and reducing pumping losses. (iii) Hybridization with electrified processes—particularly green-hydrogen production via solar-thermochemical cycles or solid-oxide electrolysis—will broaden the role of solar thermal energy from heat-only supply to a multi-vector decarbonization tool. (iv) Digitalization, including AI-based forecasting, model-predictive control, and digital-twin condition monitoring, will improve plant availability and lifetime under variable irradiance. (v) Finally, deeper integration with industrial decarbonization roadmaps, supported by standardized performance metrics (LCOH, solar fraction, capacity factor) and consistent life-cycle accounting, will be essential for solar thermal energy to scale from demonstration projects to a mainstream, gigawatt-scale heat supply technology.

7. Conclusions

This review has presented a comprehensive overview of solar thermal technologies and their applications using a temperature-oriented framework. By classifying solar thermal systems according to the quality of thermal energy they deliver, the review highlights the fundamental relationship between operating temperature, collector functionality, and application suitability. This perspective offers a practical alternative to conventional technology-centered classifications and supports more informed system selection and design.

Low-temperature solar thermal systems are well suited for residential and building-related applications, benefiting from simplicity, reliability, and cost-effective integration. Medium-temperature systems expand the applicability of STE to a wide range of industrial and cooling applications, albeit with increased design and control requirements. High-temperature solar thermal systems enable power generation and advanced industrial processes, offering unique advantages when combined with TES, despite their higher technical complexity.

Across all temperature regimes, system performance is strongly influenced by design and integration factors such as optical efficiency, HTF selection, storage compatibility, and control strategy. Addressing these factors holistically is essential for maximizing the technical and economic potential of solar thermal systems. By organizing existing knowledge around heat quality and application demands, this review provides a clear and accessible framework for researchers, engineers, and practitioners seeking to deploy solar thermal technologies effectively.

Author Contributions

Each author contributed to the article equally. B.D.: Final Draft, reviewing, submission; M.A.: First draft; A.A. (Abdulrahman Alhajeri): Background research; A.A. (Amani Alajmi) Background Research; H.G.: conceptualization, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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