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Performance Analysis and Applicability of Molten Salt Thermal Energy Storage in Different Solar Power Plant Technologies

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Abstract

Introduction:

Molten-salt thermal energy storage (TES) enables concentrated solar power (CSP) plants to store high-temperature heat efficiently and deliver dispatchable solar power. Because molten salts operate reliably between roughly 290-565 °C, their suitability varies across solar technologies with different temperature requirements, making a comparative assessment essential.

Objectives:

This study evaluates how molten-salt TES performs across solar power plant types and identifies the operational and economic conditions under which molten salts provide clear advantages.

Methods:

Thermophysical data, heat-loss modeling, degradation behavior, and system-level performance analyses from commercial CSP plants were reviewed. These results were compared to operational requirements in trough CSP, tower CSP, PV systems, and low-temperature solar thermal applications.

Results:

Findings show that molten-salt TES enables trough CSP plants to maintain full-load operation for 6-12 hours after sunset and can increase annual capacity factors from 25% to higher than 50% when storage is adequately sized. In tower CSP systems, direct molten-salt receivers achieve operating temperatures near 565 °C, supporting higher turbine efficiency and improving round-trip thermal performance. Long-duration tank studies indicate cooling rates of only around 1 °C/day, with monthly losses remaining below 30-35 K under proper insulation, confirming the feasibility of multi-day or seasonal storage. By contrast, PV modules operate at only 25-70 °C, far below the 290 °C freezing point of Solar Salt, making molten-salt TES technically impractical in PV-based systems.

Conclusions:

Molten-salt TES is a robust and efficient storage approach for high-temperature solar thermal technologies, particularly tower CSP, where it enhances dispatchability and overall system efficiency. Its application to PV and low-temperature solar thermal systems is limited by fundamental temperature incompatibilities, though opportunities remain in hybrid and high-temperature renewable-energy systems.

keyword: Molten-salt, Energy Storage, Parabolic trough, Solar tower, Solar System

1. Introduction

The rapid decarbonisation of the power sector has led to an unprecedented deployment of variable renewable energy sources, particularly solar photovoltaics (PV) and wind power. While these technologies have achieved substantial cost reductions, their variability on diurnal and seasonal timescales creates challenges for maintaining power system reliability and matching supply with demand. In this context, solar thermal technologies, especially concentrated solar power (CSP), occupy a unique niche because they can integrate thermal energy storage (TES) directly into the power block, enabling dispatchable renewable electricity [1], [2].

Globally, CSP remains a relatively small but strategically important contributor to solar generation. REN21 reports that global CSP capacity reached about 6.7 GW by the end of 2023, with substantial new deployment in regions with high direct normal irradiance such as the Middle East, China, North Africa and Spain. Although this capacity is modest compared to PV, CSP plants equipped with TES can provide several hours of firm, dispatchable power, which becomes increasingly valuable as PV penetration grows and evening net-load peaks intensify. Policy frameworks in some jurisdictions now explicitly recognise this value, for example by encouraging or requiring thermal storage in new CSP projects to enhance grid flexibility [3].

A central advantage of CSP is that the solar resource is first converted into high-temperature heat, which can be stored more economically over multi-hour timescales than electricity. Modelling studies of high-renewable power systems show that CSP with TES competes primarily with other storage technologies, particularly batteries, rather than with PV generation itself [3]. Thermal energy storage decouples solar collection from power generation, allowing CSP plants to operate at higher capacity factors and to shift output into evening and night-time hours without the efficiency penalties associated with multiple energy conversions [4]. As sensible heat storage [6]:

$$Q_{\text{sens}} = m\, c_p\, \Delta T, \qquad (1)$$

where m is the mass of the storage material, c_p is its specific heat capacity, and ΔT is the temperature difference between the hot and cold states. Latent heat storage employs PCMs that absorb or release heat at nearly constant temperature during phase transition, achieving higher storage densities but often at lower operating temperatures. Thermochemical storage relies on reversible chemical reactions, offering very high theoretical energy densities but currently faces challenges in kinetics, reactor design and system complexity. Among these options, high-temperature sensible heat storage using molten salts is the most mature and widely implemented TES technology in commercial CSP plants [7].

Nitrate-based molten salts, particularly the binary eutectic mixture commonly known as Solar Salt (60 wt% $NaNO_3$-40 wt% KNO_3), have emerged as the reference storage medium for current CSP plants. These salts offer a favourable combination of properties: relatively low cost, non-flammability, negligible vapour pressure at operating temperatures, and good compatibility with steel alloys when properly managed. Solar Salt exhibits a melting point around 220-240 °C and is typically operated between about 290 °C and 565 °C in two-tank storage systems, matching well with the temperature levels of state-of-the-art parabolic-trough and tower CSP plants [4]. In this range, reported specific heat capacities are on the order of 1.4-1.6 kJ kg^{-1} K^{-1} and densities around 1700-1900 kg m^{-3}, giving volumetric energy densities of several hundred kWh m^{-3} [8]. A convenient measure of volumetric storage capacity is

$$E_v = \rho\, c_p\, (T_{\text{hot}} - T_{\text{cold}}), \qquad (2)$$

where ρ is the density of the molten salt, and T_{hot} and T_{cold} are the hot and cold tank operating temperatures, respectively. Equations (1) and (2) highlight why molten nitrate salts are attractive: high specific heat, substantial allowable temperature swing and relatively high density translate into compact, cost-effective storage volumes for multi-hundred-megawatt CSP plants.

However, the high freezing point and the need to avoid crystallisation impose strict minimum temperature constraints on plant operation. To prevent solidification of Solar Salt in piping and tanks, commercial plants typically maintain cold-tank temperatures above 280-290 °C and ensure heat-tracing and circulation during standby periods. These constraints, combined with corrosion issues at elevated temperatures and the trade-off between higher cycle efficiency and accelerated material degradation, define a relatively narrow but critical operating window for current nitrate-salt systems [9].

The suitability of molten salt TES is therefore strongly dependent on the underlying solar power technology. CSP plants, especially central-receiver and modern parabolic-trough systems, operate naturally in the 300-600 °C range, making them well aligned with nitrate-salt properties and enabling efficient thermal coupling between the solar field, TES system and power block. In contrast, PV systems convert sunlight directly into electricity and operate near ambient module temperatures (typically 25-75 °C), so storing energy as

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high-temperature heat in molten salts would require an additional electrical-to-thermal conversion step, incurring significant efficiency penalties. Consequently, battery storage, predominantly lithium-ion, is the preferred option in PV-dominated systems [3].

At the other end of the temperature spectrum, low-temperature solar thermal applications such as domestic hot water, space heating, solar drying and building integration typically operate below about 120-150 °C [10]. In this regime, PCMs with melting points tailored to the desired operating temperatures offer high storage densities and nearly isothermal behaviour, and have been widely studied and implemented for building and solar-thermal applications. Molten nitrate salts, by contrast, would be solid in most of this temperature range and are therefore unsuitable as primary storage media for low-temperature solar thermal systems [10].

These differences underline the need for a systematic assessment of where molten salt TES is technically and economically advantageous and where alternative storage concepts, such as batteries or low-temperature PCMs, are more appropriate. While several reviews have addressed TES technologies in general or have focused on materials development for CSP, there is still a gap in the literature regarding a cross-technology comparison that explicitly links molten-salt TES performance and constraints to the operating conditions of different solar power plant types (CSP, PV and hybrid configurations) [4].

The present review aims to fill this gap by providing a focused analysis of molten salt thermal energy storage for solar power applications, with particular emphasis on (i) thermophysical properties and performance metrics of nitrate-based molten salts, (ii) their implementation and performance in commercial and near-commercial CSP plants, and (iii) their applicability and limitations when considered for other solar technologies, including PV-dominated and low-temperature solar thermal systems. Figure 1 sketches a representative CSP plant with a two-tank molten-salt TES system, highlighting the interfaces between the solar field, storage system and power block, based on typical configurations reported in the CSP literature [4].

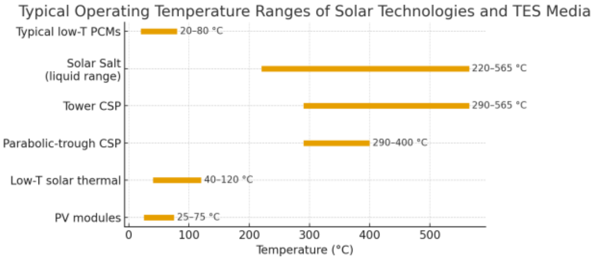

Figure 1. Schematic configuration of a tower CSP plant with a two-tank molten salt TES system, showing heliostat field, receiver, hot and cold tanks, steam generator and power block.

2. Fundamentals of Thermal Energy Storage and Molten Salt Materials

TES enables time-shifting of heat supply and demand in solar systems and is conventionally classified into sensible, latent and thermochemical concepts. Sensible heat storage uses the temperature change of a medium (molten salts, rocks, concrete), latent heat storage exploits phase transitions of PCMs, and thermochemical storage relies on reversible chemical reactions or sorption processes [11]. Figure 2 summarises this classification. For solar power plants, sensible heat storage in molten salts is by far the most mature high-temperature option and is widely implemented in commercial CSP projects.

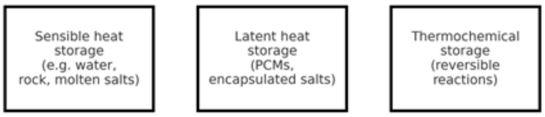

Figure 2. Main categories of thermal energy storage technologies.

In many CSP plants, molten salts are used either alone (two-tank sensible storage) or in combination with solid fillers (thermocline or packed-bed systems). In such composite media, it is useful to define an effective volumetric heat capacity that accounts for both the solid matrix and the molten salt. For a packed bed with porosity ε(fraction of volume occupied by fluid), the effective volumetric heat capacity can be written as [12]:

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$$(\rho c_p)_{\mathrm{eff}} = (1 - \varepsilon)\, \rho_{\mathrm{s}} c_{p,s} + \varepsilon\, \rho_{\mathrm{f}} c_{p,\mathrm{f}} \qquad (3)$$

where $\rho_s, c_{p,s}$are the density and specific heat of the solid filler (rock, ceramic, slag), and $\rho_{\mathrm{f}}, c_{p,\mathrm{f}}$are those of the molten-salt fluid. This relation is widely used in modelling of packed-bed and thermocline TES, and it shows that high-density, high-c_p fillers can significantly increase the overall storage capacity while reducing salt inventory and cost.

The thermal and chemical stability of nitrate-based molten salts is another key aspect. Solar Salt, approximately 60 wt% $NaNO_3$ and 40 wt% KNO_3, undergoes decomposition at elevated temperatures via nitrate-to-nitrite reduction with oxygen release.

Measurements on Solar Salt and related nitrate mixtures report activation energies in the range of roughly 90-130 kJ mol^{-1} for nitrate decomposition, indicating a strong temperature sensitivity of degradation processes.

From a materials perspective, Solar Salt offers a favourable balance of properties for current CSP plants: a liquidus temperature around 220-240 °C, practical operation between approximately 290 and 565 °C, specific heat capacities of 1.4-1.6 kJ kg^{-1} K^{-1} and densities near 1700-1900 kg m^{-3}. When these values are combined with realistic temperature spans in actual plants, the resulting volumetric energy density is of order a few hundred kWh m^{-3}, significantly higher than that of water over typical low-temperature ranges and comparable to or better than many low-temperature PCMs on a volumetric basis.

However, the same properties that make molten salts attractive also impose stringent operating constraints. The high melting point requires that the cold-tank and piping temperatures be kept safely above the freezing temperature, typically using heat-tracing and careful operating procedures; if the salt freezes, costly and time-consuming recovery operations are needed. At the upper end of the temperature range, faster decomposition and higher corrosion rates, following the Arrhenius behaviour in Eq. (2.2), limit operation to about 565-600 °C for nitrate salts when using conventional steel alloys. These constraints are central to plant-level design and are revisited later when discussing system configurations and future high-temperature salt candidates.

In summary, this section emphasises material-level fundamentals that underlie molten-salt TES performance: composite effective heat capacity in practical storage configurations and temperature-dependent degradation kinetics. Together with the thermophysical property data synthesised from the literature, they provide the basis for analysing system-level configurations and performance, which are examined in the next section.

3. Molten-Salt Thermal Energy Storage Configurations and Performance in CSP Plants

The integration of molten-salt TES into CSP plants has transformed their operational flexibility, stability, and overall efficiency. The uploaded references provide detailed engineering evidence that molten-salt TES is a mature, technically reliable solution capable of supporting multi-hour dispatchable operation. Its success arises from the high thermal capacity, stable thermophysical properties, and low vapor pressure of nitrate-based salts, which allow the design of atmospheric, large-volume storage tanks that operate safely and efficiently at elevated temperatures.

In parabolic trough plants, TES is commonly implemented through an indirect two-tank configuration. This arrangement is demonstrated in Figure 3, taken from Herrmann et al. (2004), which outlines the principal components of the system. During charging, the HTF, typically a synthetic oil circulating through the collector field, transfers thermal energy to molten salt via an oil-to-salt heat exchanger. The molten salt is then stored in a hot tank at approximately 385 °C. During discharging, the thermal energy is returned to the HTF, supplying the power block even when solar radiation is insufficient. This configuration was extensively analyzed based on the operational history of the SEGS and Solar Two projects, and Herrmann et al. [13] report that the system demonstrated robust technical performance with no significant barriers to implementation in commercial trough plants.

A notable outcome of the engineering study is the way molten-salt TES supports increased storage capacity at reasonable cost. Herrmann et al. [13] quantified the

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scaling of salt inventory, pump power, tank dimensions, insulation characteristics, and heat-exchanger requirements for storage sizes ranging from 1 to 15 hours. Their simulation work showed that plants equipped with larger storage volumes experience substantial increases in annual full-load operating hours, in some cases doubling their effective utilization compared with plants lacking storage. The two-tank concept, which operates at atmospheric pressure due to the negligible vapor pressure of molten salts, also eliminates the safety challenges associated with pressurized oil systems. The design of the tank foundation, comprising fire bricks, foamglass insulation, thermal slabs, and steel liners, was shown to limit downward heat losses effectively, keeping the storage medium safely above its freezing point even during prolonged standby periods.

Although the indirect system is suitable for trough plants, molten-salt TES reaches maximum effectiveness in central receiver (tower) CSP systems, where molten salt itself is circulated through the receiver. The direct two-tank configuration illustrated in Figure 4, extracted from Prieto et al. [14], depicts the arrangement in which cold salt is pumped to the top of the tower, heated by concentrated flux, and then stored in the hot tank at temperatures approaching 565 °C. Operating molten salt directly in the receiver eliminates the need for an intermediate HTF and reduces thermal losses associated with additional heat-exchanger stages. This higher operating temperature has significant implications for power-block performance, as the elevated turbine inlet temperature increases the thermal efficiency of the Rankine cycle commonly used in CSP power blocks.

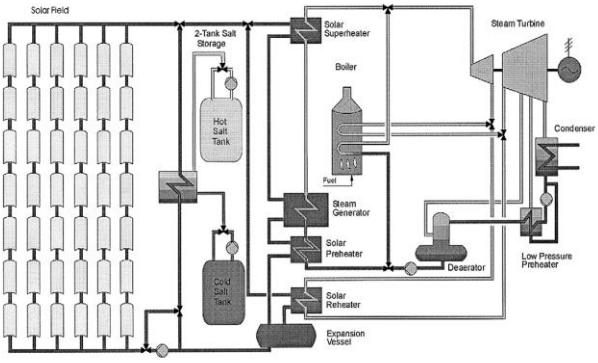
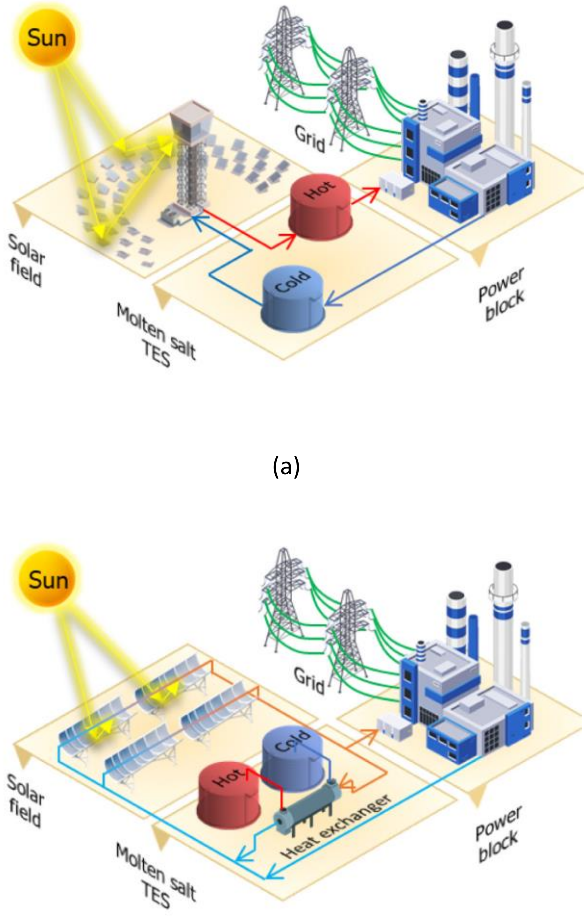


Figure 3. Schematic flow diagram of a parabolic trough plant with two-tank molten-salt storage system (Herrmann et al. [13]).



(a)

(b)

Figure 4. Direct and indirect molten-salt TES configurations for tower CSP systems (Prieto et al. [14]).

Prieto et al. [14] provide a detailed analysis of heat-loss mechanisms in molten-salt tanks, considering wall conduction, roof losses, bottom conduction, convection, and local assembly defects. Their results demonstrate that well-insulated tanks exhibit daily cooling rates close to 1 K/day, and the temperature decay follows an asymptotic trend with increasing insulation thickness. When insulation thickness approaches practical construction limits, monthly temperature reductions remain within approximately 14-37 K, depending on whether construction imperfections are included in the analysis. Importantly, their measurements show that heat losses occur predominantly through the molten salt itself rather than through tank structures or cover gas. These findings indicate that molten-salt TES tanks are thermally stable over durations extending well beyond

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the diurnal cycle, enabling not only daily storage but also longer-duration buffering.

The operational stability of molten-salt thermal energy storage has major implications for the overall performance of concentrated solar power plants. Because molten salts maintain stable thermophysical properties under repeated cycling between 290 and 565 °C, they allow CSP power blocks to operate at nearly constant inlet conditions even when the solar field is unable to supply direct heat. This stability has been demonstrated across numerous plant-scale studies. Herrmann et al. [13] showed through detailed simulations of parabolic trough plants that storage capacities in the range of 6-12 hours enable sustained full-load operation for extended periods after sunset, significantly increasing dispatchable output. Their findings are consistent with later analyses of commercial trough systems, including those reported for the Andasol complex in Spain, where multi-hour molten-salt storage nearly doubled the annual full-load equivalent hours relative to a no-storage configuration [15].

Central-receiver (tower) CSP plants benefit even more from molten-salt TES because molten salt acts directly as the heat-transfer fluid in the receiver, eliminating intermediary thermal stages and yielding higher hot-tank temperatures. As a result, power-block efficiency remains high even when the plant operates entirely on stored energy. Long-term performance assessments from demonstration and commercial tower plants, including Solar Two, Gemasolar, Crescent Dunes, and Noor III, confirm that molten-salt loops exhibit predictable thermal behavior with minimal degradation. The experimental and simulated results of Prieto et al. support this evidence by showing that thermal losses in large molten-salt tanks are dominated by well-characterized conduction and convection pathways that can be managed effectively with proper insulation design. Their quantified cooling rates, typically close to 1 K per day, validate that molten-salt TES can sustain multi-hour to multi-day storage without compromising turbine inlet conditions.

The ability of tower plants to maintain storage temperatures above 550 °C also improves the performance of the Rankine cycle, and in advanced designs, supports integration with supercritical CO_2 Brayton cycles. Studies by Neises and Turchi [16] demonstrate that molten-salt TES operating in this high-temperature region enables substantial efficiency gains, further enhancing the competitiveness of tower CSP relative to other dispatchable renewable options. These improvements in conversion efficiency, combined with the high round-trip thermal efficiency of molten-salt systems, contribute to the overall economic value of molten-salt storage.

Field data and model-based evaluations agree that molten-salt TES enhances CSP plant resilience, particularly during weather variability, seasonal irradiance dips, or operational contingencies. Case studies reported by Kolb et al. [17] demonstrate how molten-salt towers maintain turbine operation during multi-hour cloud cover, while long-term measurements from Gemasolar highlight the capability of operating continuously for 24 hours under favorable conditions. These operational results confirm the strong synergy between molten-salt TES and tower architectures, establishing them as reliable long-duration dispatch systems.

Across the range of CSP technologies examined, molten-salt TES consistently emerges as an indispensable element in achieving stable, dispatchable solar power. It reduces the mismatch between solar availability and grid demand, smooths transient solar-field behavior, and improves year-round capacity factors. The accumulated operational history of both trough and tower systems, supported by validated thermal models and more than two decades of plant-scale data, demonstrates that molten-salt TES is a proven, scalable, and economically robust storage technology for current and next-generation solar thermal applications.

4. Applicability of Molten-Salt Thermal Energy Storage Across Different Solar Power Technologies

The applicability of molten-salt TES depends fundamentally on the temperature range of the solar technology, the manner in which thermal energy is collected or converted, and the operational role storage is expected to play. Although molten salts have become a defining component of CSP systems, their integration into other solar technologies remains highly constrained. A synthesis of the uploaded engineering studies, together with external literature, clarifies the

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conditions under which molten-salt TES is technically feasible, economically advantageous, or incompatible.

In parabolic trough CSP plants, molten-salt TES is used in an indirect configuration in which synthetic oil acts as the HTF. Herrmann et al. [13] demonstrated that molten-salt storage is well aligned with the thermal characteristics of trough plants, given that typical HTF outlet temperatures of around 390 °C fall comfortably within the operational window of nitrate-based salts. Their system-level simulations revealed that incorporating 6-12 hours of molten-salt storage substantially increase the annual number of full-load operating hours and reduces the levelized cost of electricity. The technical results from Herrmann et al. [13] were validated through reference to the operational experience of early hybrid CSP plants such as SEGS and Solar Two, establishing that molten-salt TES can be implemented without imposing significant structural or thermal design complications.

The suitability of molten-salt storage is even more pronounced in central-receiver (tower) CSP plants, where molten salt commonly serves as the primary HTF. Operating temperatures in the receiver typically range from 550 °C to 565 °C, which not only fall within the thermal stability limits of Solar Salt but also support higher thermodynamic efficiency at the steam turbine. Prieto et al. [14] argue that the synergy between tower receivers and molten-salt TES is one of the central reasons why tower plants have become the preferred configuration for CSP projects requiring long-duration storage. Their analysis of heat-loss mechanisms and long-duration thermal behavior shows that molten-salt tanks cool slowly over time, typically around 1 K per day, provided that insulation is properly designed.

While molten-salt TES aligns naturally with high-temperature CSP technologies, its application in PV systems is not technically viable. PV modules generate electricity directly, with operating temperatures usually between 25 °C and 70 °C, far below the melting point of Solar Salt. Integrating molten-salt TES into a PV system would require conversion of electricity back into heat and then raising the temperature of the molten salt to at least 290 °C to avoid freezing. Such a process would involve significant energy losses and expensive high-temperature infrastructure, making it economically and thermodynamically inferior to electrochemical batteries. Numerous system-comparison studies, including those by Jülch [18] and Ziegler et al. [19], confirm that battery storage is the optimal technology for PV because it preserves electricity in its original form and avoids the conversion penalties that would arise in a PV-molten salt arrangement.

The limits of molten-salt applicability become even clearer when considering low-temperature solar thermal applications. Domestic water heating, space conditioning, and industrial processes below 150 °C commonly rely on sensible water storage or latent-storage systems using PCMs. Zalba et al. [20] and Cabeza et al. [21] show that these technologies are superior at low temperatures due to their lower cost, simpler containment requirements, and suitability for building-integrated installations. In contrast, molten salts would be permanently solid in such systems, and maintaining tank temperatures above the melting point would require continuous external heating, eliminating any energy-saving benefit. The uploaded engineering analyses reinforce this conclusion: Prieto et al. [14] show that heat losses from molten-salt tanks remain manageable only when the tank operates above 250 °C, highlighting the incompatibility of molten salts with low-temperature solar cycles.

There is, however, a growing interest in whether molten-salt TES can serve broader roles in hybrid or high-temperature energy systems. Feldhoff et al. [22] evaluate hybrid CSP-biomass plants and argue that molten-salt storage can effectively buffer fluctuations from variable biomass supply or enhance baseload characteristics. Similarly, Turchi et al. [23] show that molten salts remain compatible with advanced power cycles, particularly supercritical CO_2 cycles, which could operate at temperatures beyond the nitrate limit if alternative, higher-temperature salts are used. These studies expand the potential applicability of molten salts within energy system configurations that rely on high-temperature thermal input rather than direct solar heating. Nonetheless, such integration still requires heat sources capable of maintaining the salt in its liquid phase.

Beyond CSP, researchers have explored molten-salt storage as a grid-scale thermal energy storage medium for long-duration or seasonal storage when coupled to high-temperature resistive heating. Cui et al. [24] point out that molten-salt TES could serve as a viable solution in renewable-heavy grids, where excess wind or solar

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electricity can be converted into heat and stored for extended periods. However, these scenarios still require infrastructure designed for temperatures far above those typical of PV or building-scale solar installations, and thus do not modify the conclusion that molten-salt TES is fundamentally a high-temperature technology.

Taken together, the evidence demonstrates that molten-salt TES is technically and economically suited for CSP, particularly tower plants, and remains a poor fit for PV or low-temperature solar thermal systems. Its integration in hybrid high-temperature systems is promising but contingent on the availability of heat sources capable of maintaining high operating temperatures. As solar technologies continue to evolve, molten-salt TES is expected to maintain its leading role in high-temperature solar thermal applications while remaining peripheral in low-temperature or fully electrical systems.

5. Conclusion

Molten-salt thermal energy storage has emerged as one of the most mature and effective technologies for enabling dispatchable solar electricity generation, particularly in CSP systems that operate within high-temperature regimes. The thermophysical properties of nitrate-based molten salts, high specific heat capacity, thermal stability up to approximately 565 °C, low vapor pressure, and compatibility with large atmospheric tanks, enable multi-hour to multi-day storage with relatively low thermal losses. These characteristics allow CSP plants to decouple solar energy collection from electricity production, ensuring that generation can be matched more closely to demand profiles and improving both capacity factor and grid integration.

Parabolic trough plants have demonstrated the feasibility of integrating molten-salt TES through indirect two-tank systems that transfer heat from a synthetic-oil field to the storage medium. The analysis of these systems, supported by engineering assessments and operational evidence, shows that storage capacities of six hours or more significantly enhance turbine utilization, reduce sensitivity to intermittent irradiance, and lower levelized electricity cost. Tower CSP plants achieve even greater performance benefits because molten salt works as heat-transfer fluid and storage medium, reaching temperatures near 565 °C without requiring intermediate fluids. This direct configuration minimizes irreversible thermal losses, supports higher power-cycle efficiency, and has been validated in commercial projects operating worldwide.

The broader applicability of molten-salt TES is shaped by the strict temperature requirements of the storage medium. Photovoltaic systems, which operate near ambient temperature, and low-temperature solar thermal systems, typically below 150 °C, cannot utilize molten-salt TES without unacceptable thermodynamic penalties or major engineering modifications. In these contexts, electrochemical or phase-change storage technologies remain more suitable. Conversely, hybrid high-temperature systems, such as CSP coupled with biomass, supercritical CO_2 cycles, or resistive heating driven by renewable surplus, offer potential future pathways for molten-salt TES, provided that the heat source maintains the salt within its liquid-phase temperature range.

The findings presented in this study reinforce the conclusion that molten-salt TES remains uniquely aligned with high-temperature solar thermal technologies, especially tower CSP architectures designed for long-duration dispatchability. Its demonstrated thermal stability, predictable cooling behavior, and scalability to multi-megawatt-hour capacities provide a robust foundation for continued deployment. As renewable grids incorporate larger shares of variable resources, the ability of molten-salt TES to deliver flexible, high-temperature thermal energy positions it as a cornerstone technology for future dispatchable solar power plants and emerging high-temperature storage applications. Continued improvements in insulation, tank design, and advanced salt formulations will further extend its performance envelope, ensuring its relevance in the evolving landscape of renewable energy storage.

References

[1] L. C. C. Gonçalves and S. D. Probert, “Thermal-energy storage: Dynamic performance characteristics of cans each containing a phase-change material, assembled as a packed-bed,” *Appl Energy*,

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* Corresponding author, Email address: Hani.youssef.cku@atu.edu.iq

vol. 45, no. 2, 1993, doi: 10.1016/0306-2619(93)90040-V.

[2] A. Caraballo, S. Galán-Casado, Á. Caballero, and S. Serena, "Molten Salts for Sensible Thermal Energy Storage: A Review and an Energy Performance Analysis," *Energies 2021, Vol. 14, Page 1197*, vol. 14, no. 4, p. 1197, Feb. 2021, doi: 10.3390/EN14041197.

[3] K. M. Kennedy *et al.*, "The role of concentrated solar power with thermal energy storage in least-cost highly reliable electricity systems fully powered by variable renewable energy," *Advances in Applied Energy*, vol. 6, 2022, doi: 10.1016/j.adapen.2022.100091.

[4] F. Alnaimat and Y. Rashid, "Thermal energy storage in solar power plants: A review of the materials, associated limitations, and proposed solutions," 2019. doi: 10.3390/en12214164.

[5] B. M. Tripathi, S. K. Shukla, and P. K. S. Rathore, "A comprehensive review on solar to thermal energy conversion and storage using phase change materials," 2023. doi: 10.1016/j.est.2023.108280.

[6] A. Bejan, *Advanced Engineering Thermodynamics*. 2016. doi: 10.1002/9781119245964.

[7] P. Tatsidjodoung, N. Le Pierrès, and L. Luo, "A review of potential materials for thermal energy storage in building applications," 2013. doi: 10.1016/j.rser.2012.10.025.

[8] B. D'Aguanno, M. Karthik, A. N. Grace, and A. Floris, "Thermostatic properties of nitrate molten salts and their solar and eutectic mixtures," *Sci Rep*, vol. 8, no. 1, 2018, doi: 10.1038/s41598-018-28641-1.

[9] X. Liu, Y. Zhong, J. Li, H. Wang, and M. Wang, "A Review of High-Temperature Molten Salt for Third-Generation Concentrating Solar Power," *Energy Sci Eng*, vol. 13, no. 2, pp. 456–474, Feb. 2025, doi: 10.1002/ESE3.2029;REQUESTEDJOURNAL:JOURNAL:20500505;PAGE:STRING:ARTICLE/CHAPTER.

[10] G. Hameed *et al.*, "Low temperature phase change materials for thermal energy storage: Current status and computational perspectives," *Sustainable Energy Technologies and Assessments*, vol. 50, 2022, doi: 10.1016/j.seta.2021.101808.

[11] S. Pascual, P. Lisbona, and L. M. Romeo, "Thermal Energy Storage in Concentrating Solar Power Plants: A Review of European and North American R&D Projects," 2022. doi: 10.3390/en15228570.

[12] M. Majó, A. Svobodova-Sedlackova, A. I. Fernández, A. Calderón, and C. Barreneche, "Thermal Cycling Test of Solar Salt in Contact with Sustainable Solid Particles for Concentrating Solar Power (CSP) Plants," *Energies 2024, Vol. 17, Page 2349*, vol. 17, no. 10, p. 2349, May 2024, doi: 10.3390/EN17102349.

[13] U. Herrmann, B. Kelly, and H. Price, "Two-tank molten salt storage for parabolic trough solar power plants," *Energy*, vol. 29, no. 5–6, pp. 883–893, Apr. 2004, doi: 10.1016/S0360-5442(03)00193-2.

[14] C. Prieto, P. D. Tagle-Salazar, D. Patiño, J. Schallenberg-Rodriguez, P. Lyons, and L. F. Cabeza, "Use of molten salts tanks for seasonal thermal energy storage for high penetration of renewable energies in the grid," *J Energy Storage*, vol. 86, 2024, doi: 10.1016/j.est.2024.111203.

[15] S. Kuravi, J. Trahan, D. Y. Goswami, M. M. Rahman, and E. K. Stefanakos, "Thermal energy storage technologies and systems

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* Corresponding author, Email address: Hani.youssef.cku@atu.edu.iq

for concentrating solar power plants," 2013. doi: 10.1016/j.pecs.2013.02.001.

[16] T. Neises and C. Turchi, "Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650 °C," *Solar Energy*, vol. 181, pp. 27–36, Mar. 2019, doi: 10.1016/J.SOLENER.2019.01.078.

[17] P. Viebahn *et al.*, "Power Tower Technology Roadmap and cost reduction plan.," *Energy Policy*, vol. 14, no. September, pp. 5–7, Apr. 2011, doi: 10.2172/1011644.

[18] V. Jülch, "Comparison of electricity storage options using levelized cost of storage (LCOS) method," *Appl Energy*, vol. 183, pp. 1594–1606, Dec. 2016, doi: 10.1016/J.APENERGY.2016.08.165.

[19] M. S. Ziegler *et al.*, "Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization," *Joule*, vol. 3, no. 9, 2019, doi: 10.1016/j.joule.2019.06.012.

[20] B. Zalba, J. M. Marín, L. F. Cabeza, and H. Mehling, "Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications," 2003. doi: 10.1016/S1359-4311(02)00192-8.

[21] L. F. Cabeza, A. Castell, C. Barreneche, A. De Gracia, and A. I. Fernández, "Materials used as PCM in thermal energy storage in buildings: A review," 2011. doi: 10.1016/j.rser.2010.11.018.

[22] J. F. Feldhoff *et al.*, "Comparative system analysis of direct steam generation and synthetic oil parabolic trough power plants with integrated thermal storage," *Solar Energy*, vol. 86, no. 1, pp. 520–530, Jan. 2012, doi: 10.1016/J.SOLENER.2011.10.026.

[23] C. S. Turchi, Z. Ma, T. W. Neises, and M. J. Wagner, "Thermodynamic study of advanced supercritical carbon dioxide power cycles for concentrating solar power systems," *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 135, no. 4, 2013, doi: 10.1115/1.4024030.

[24] Y. Cui, K. Jiang, H. Wei, L. Xu, and X. Du, "Flexible thermal power units integrated with molten salt thermal storage: Thermal energy distribution active adjustment method and thermodynamic evaluation," *J Energy Storage*, vol. 117, p. 115983, May 2025, doi: 10.1016/J.EST.2025.115983.

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