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Progress and Prospects of TES for Central Receiver-Based CSP Plants

Brenda Hernandez Corona[1], Matteo Chiesa[1,*], Nicolas Lopez Ferber[1], Ahmad Mayyas[1], and Nicolas Calvet[1,2]

[1]Khalifa University, United Arab Emirates.

[2]Present address: NEOM, Saudi Arabia

*Correspondence: Dr. Matteo Chiesa, matteo.chiesa@ku.ac.ae

Abstract. This review categorizes the thermal energy storage (TES) technologies—sensible heat, latent heat, and thermochemical storage—and evaluates their development, application, and performance within central receiver-based concentrated solar power plants. This study explores the progression of TES systems, delineating the evolution from technologies such as saturated steam and molten salt, first used in the Eurelios power plant in 1980 as a protective storage solution for 30 minutes, to commercial molten salt storage capacities of up to 15 hours. This study also examines emerging research and development technologies aimed at achieving higher efficiencies and operating temperatures. The objective is to identify technological trends, assess the efficacy of different TES systems, and highlight future directions for research and application.

Keywords: CSP, Central Receiver Based Plants, TES

1. Introduction

The race towards reliable renewable energy sources is accelerating in the pursuit of fulfilling the Sustainable Development Goals (SDGs) [1]. One of the greatest challenges remains the intermittency of renewable sources such as solar and wind. Notably, high-temperature concentrated solar power (CSP) is being studied for its capacity of integration with thermal energy storage (TES), which captures energy during periods of high direct normal irradiance (DNI) and retains it to mitigate solar resource intermittency, ensuring dependability and adaptable power generation in CSP plants [2].

Historically, TES systems have evolved from early steam-based designs, such as those used in the Eurelios power plant in the 1980s [3], to commercial two-tank molten salt storage systems first implemented in Gemasolar in 2011 [4] and the recent and under-construction deployments in the Middle East and China [5]. The construction of solar towers from 2021 to the present accounts for the highest development ratio of solar towers in the past decade, considering historically the NREL database of CSP projects [6]. Over time, advancements in CSP, particularly TES, have extended storage durations from less than one hour in early designs to over 14 hours, significantly extending the operational period of CSP plants. However, challenges in the technology, such as the need for higher operational temperatures, system complexity reduction, and improving the long-term durability of TES materials, still persist and are the focus of the research community.

This work explores the research done to overcome current challenges and identify future prospects for central receiver CSP applications. Investigating alternate materials, such as chloride salts [7] and particle-based [8] storage systems, makes it possible to achieve higher operational temperatures and enhance efficiency. Also, thermochemical storage (TCS) [9], phase change materials (PCM) [10], and thermocline systems [11] are gaining attention due to their potential for higher energy density and longer storage durations. However, these technologies are still in the R&D and testing phase for central receiver plants and require further investigation before large-scale commercial deployment.

This paper aims to provide a comprehensive review of the various TES technologies utilized in central receiver-based CSP plants. Specifically, the study categorizes TES technologies into sensible heat, latent heat, and thermochemical storage systems and evaluates their application and performance. The paper also examines emerging research trends that enhance TES system efficiency, reduce costs, and facilitate higher-temperature operations. The ultimate goal is to assess technological progress and identify future research pathways that can drive innovation in the field of TES for CSP.

2. Historical Overview and Technological Evolution

The classification of central receiver based CSP plants outlines the evolution of TES component. At the beginning pilot plants did not integrate TES as early designs mainly focused on optimizing the optical systems and the solar receiver, which was placed as a static focal point at a high elevation such as St. Ilario-Nervi (1965) [12], Solar Plant No.1 (1965) [13], and Odellio Solar Furnace (1972) [14]. Eventually, methods such as saturated steam systems were limited by their storage capacity, which primarily protected against intermittent cloud coverage providing brief connectivity to the TES for approximately 30 minutes to maintain production and protect equipment, as evidenced by installations such as Eurelios [15] and PS10 [16]. Eurelios was the world's first plant to incorporate TES with a combination of steam (300 kWh) and Hitec molten salt (60 kWh) [3].

In 1982, the concept of thermocline TES was tested in Solar One [17] using synthetic oil first and converted to Solar Two with the incorporation of the two-tank molten salt configuration in the 90's using the conventional solar salt and storage capacity of three hours [18]. "Two-tank molten salt" TES systems are preferred for overnight storage due to their cost-effectiveness and excellent operational efficiencies. In 1983, THEMIS was the first testing facility to use molten salt as the heat transfer fluid (HTF) and thermal storage medium simultaneously for nighttime operation [19] and became the predecessor of the first commercial power plant with such configuration, Gemasolar, first operated in 2011 [20].

Gemasolar laid the foundation for the next generation of commercial power plants as the 2-tank molten salt became the predominant configuration adopted for future plants. Commercialization progressively enhanced storage capacity from a few hours in the early 1970s to a consistent 12-hour storage standard in the 2010s and continuing thereafter, suitable for nighttime production. However, temperature constraints are critical to ensuring the longevity and effectiveness of the storage system.

3. Technologies and Their Application

Thermal energy storage (TES) systems can be classified by their storage media into sensible heat storage, latent heat storage, and thermochemical storage. These systems are further categorized as active (direct and indirect) and passive, based on the storage concept. Central receiver TES systems have progressed over time, with the most common systems including molten salt, saturated steam, thermocline, and particle TES as presented in Figure 1. Newer systems are exploring PCM and TCS TES for central receiver-based plants.

Saturated Steam TES, an early technology, provides quick response times but faces limitations in energy storage efficiency and requires thick-walled containers due to high pressures, as seen in Planta Solar 10 (PS10). Molten Salt TES, evolving since the 1980s and exemplified by the Gemasolar plant, serves as a heat transfer fluid and storage medium, offering high thermal stability and efficiency. The ideal separation of molten salt into two tanks (one hot and one relatively cold) allows for controlled energy storage and higher efficiency in power generation [21]. This separation enables a more efficient thermodynamic cycle, reduces thermal losses, as the heat is stored and transferred only as needed, and maintains high energy conversion efficiency. The disadvantages of the system include the parasitic energy to avoid freezing salt in the piping system and the temperature constraints critical to ensuring the longevity and effectiveness of the storage system. Operational limits are set to prevent the chemical breakdown of the salts and damage to the storage infrastructure (usually between 290°C and 565°C) [22], limiting the thermal storage capacity per unit volume and the maximum yield of the power cycle located after it.

Thermocline TES features a cost-effective single-tank design that allows diverse, low-cost materials. Still, it faces the problem of slow heat transfer and temperature stability, illustrated by projects like Solar One. Particle TES has been advancing to improve heat transfer using materials like sand and ceramics, focusing on overcoming design complexities and abrasion from high-velocity flows. The graph displays the categorization based on data of TES technologies for central-receiver plants, focusing on operational and under-construction facilities. It examines the relationship between TES categories and the year of operationalization, categorized by different regions. The size of each point corresponds to the storage capacity in hours, allowing for a clear visualization of how capacity scales across projects. The color coding distinguishes between regions, making it easy to identify geographical trends. The graph highlights the development trajectory of TES technologies and their varying storage capacities across regions and time.

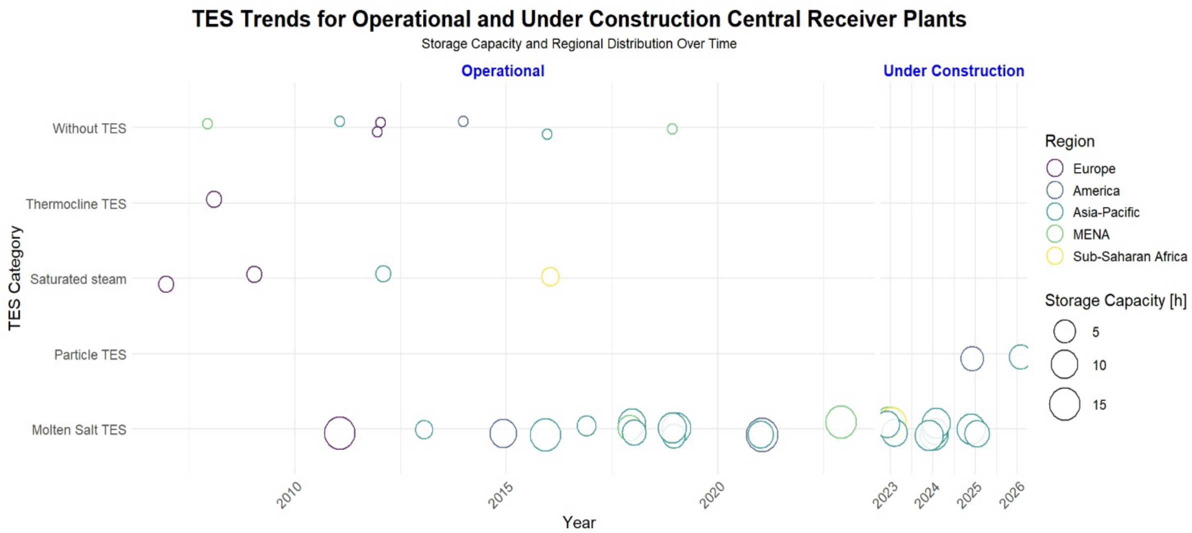

Figure 1. *TES for operational and under-construction central receiver plants ordered chronologically by technology in color and capacity in point size (Data collected from NREL [6] and CSP.guru [20] databases).*

4. Future Pathways

This section of the review intends to show the trends on TES that are or can be applicable for central receiver-based CSP. The highlights of the research work are summarized in Figure 2.

Recent innovations in TES focus on enhancing temperature resilience and reducing costs. Advanced materials such as chloride salts allowing higher operational temperatures, such as potassium chloride (KCl) and magnesium chloride ($MgCl_2$) are investigated as alternatives to nitrate salts at high temperatures (up to 800°C) [24], although they require careful management due to their corrosive nature and potential toxicity. While beneficial for high-temperature operation, chloride salts can pose risks, such as releasing toxic fumes (Cl_2) when they decompose or react with water or air [7] and higher parasitic energy consumption due to higher freezing temperatures.

Emerging designs like single-tank thermocline systems and particle-based storage offer promising alternatives with potentially lower costs and higher efficiencies. In a single-tank thermocline design, the separation between hot and cold fluid is not realized through a physical separation as in the two-tank design but using buoyancy forces [25]. Although it is possible to design a single tank with only the HTF (typically oil or nitrate molten salts), this generates some issues related to mixing and internal convection, which destabilizes the thermal gradient and tends towards a homogeneous temperature in the tank. The incorporation of a solid filler for a dual-media thermocline TES, however, reduces this drawback and adds other significant advantages [26], [27]. Solids beeing generally less expensive than HTF, adding low-cost solid filler materials to the thermocline tank allows for replacing up to 80% of the more expensive heat transfer fluid without compromising energy storage efficiency, leading to cost savings in construction and operation. As the storage function is mostly incumbent on the solid rather than the HTF, these packed bed designs are compatible with gaseous HTFs (air, CO_2, N_2, etc.), allowing the CSP plant to operate at higher temperatures. Major emerging works are the dual heat storage concept integrating two thermocline thermal energy storage units with a solar redox reactor to enhance high-temperature heat recovery [28]. Experimentally, heat extraction effectiveness of 70% was reached, and theoretical modeling for a scaled-up 50 kW reactor predicts a potential increase in solar-to-fuel efficiency to 14.7%. Finally, [29] describes the first experimental work to prove high-temperature heat recovery using a simplified single heat storage system with a honeycomb thermal energy storage unit, achieving a heat recovery effectiveness of 33%.

Integrating novel materials like basalt or industrial waste-based ceramics into TES systems presents opportunities for sustainable and economically viable solutions. The challenges of using industrial waste materials in high-temperature applications are due to their unsuitable forms and heterogeneous microstructures, which make them brittle and vulnerable; thus, cost-effective processing technologies should be studied [30], [31], [32]. Ceramics made of industrial wastes, for example, asbestos, steel slags, incinerator bottom ashes, coal fly ash, and mine tailings, among others [33], [34], [35], [36] have been investigated as potential cost-effective replacements for standard ceramics. The main objective is to overcome conventional HTF's deterioration drawbacks when exposed to temperatures over 600°C. Particle-based TES systems use solid particles as a heat-transfer medium to store heat at high temperatures (800°C or more), facilitating high-efficiency power generation, for example, using advanced power cycles like supercritical CO_2 Brayton cycles [37]. Example of particles TES is the Gen 3 Particle Pilot Plant [38]. The moving packed-bed particle TES system uses bauxite particles for high-temperature, and experimental results demonstrate thermal charging and discharging efficiencies above 85% with outlet air temperatures exceeding 700 °C [39].

Latent heat storage is highlighted for its high potential in efficiency and economy utilizing PCMs. It offers significantly higher energy density, enabling more compact storage solutions and inventory requirements [40]. CSP's first practical applications and conceptual introductions likely originated in the late 20th century as researchers explored various methods to improve efficiency and storage capabilities. Emerging technologies, for instance [41], have experimentally investigated the combined sensible–latent storage system using rocks and an encapsulated AlSi12 phase change material, demonstrating stabilized discharge temperatures of approximately 575 °C for around 90 minutes. The validated transient model confirms that adding a small PCM layer significantly improves temperature stability compared to sensible-only systems, which is particularly beneficial for downstream processes requiring consistent thermal input.

Thermochemical storage (TCS) stores solar energy through endothermic chemical reactions during the absorption phase and releases this energy via exothermic reactions during the discharge phase, offering higher energy density and the capability to store heat for extended periods without losses [9]. Current TCS technologies predominantly use redox reactions [42] involving metal oxide hydroxylation reactions or the generation of hydrogen or syngas (solar pyrolysis) [43]. Another major work on TCS is the seasonal storage, as presented in [44] where magnesium-manganese oxide-based solid-state fuel (SoFuel) was tested for long-duration, achieving solid flowability over six months at high temperature (1450°C). The system demonstrated a thermochemical efficiency of 96% and an overall system efficiency of 35%. Although they are in the interest of the CSP community in transitioning to high-temperature operation, these technologies are still in the developmental phase, primarily at the prototype or pilot scale.

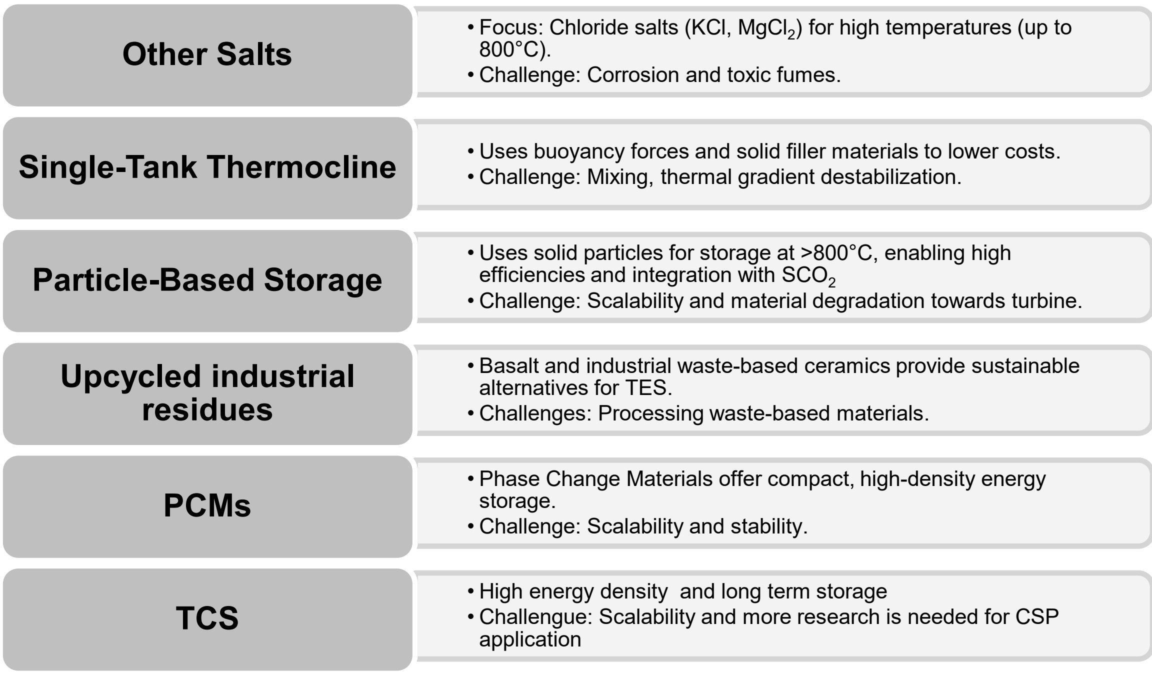

Figure 2. *TES future pathways for integration with central receiver-based CSP plants.*

5. Conclusions

The capability of integrating TES and operating at higher temperatures makes central receiver-based CSP plants highly suitable for playing a pivotal role in the current energy transition. This review demonstrates that, over time, both researchers and industry professionals have increasingly focused on developing projects aimed at enhancing the efficiency and storage capacity of existing commercial systems. Over the years, the tendency of TES has been to grow in storage capacity, and the two-tank molten salt configuration has remained the preferred choice for operational commercial projects, including the newly announced projects at the beginning of 2024 to be built in China. However, R&D keeps actively looking for ways to improve TES and to bring solutions from other applications to CSP plants. The evolution of technology shows a tendency toward increasing operational temperatures, seeking various ways to implement systems at higher temperatures, reduce costs, and gain efficiency. The future pathways may include the use of chloride or carbonate salts, single-tank thermocline TES configurations, particle-based storage, upcycled industrial residues, and the incorporation of technologies such as PCMs and TCS from other applications into central receiver-based CSP plants.

Data availability statement

The data supporting the findings of this study are publicly available. Quantitative analysis was conducted using data extracted from the National Renewable Energy Laboratory (NREL) Concentrating Solar Power Projects by Technology database [6], and the *Guru CSP* platform [20], both of which are accessible online. These sources provide open access to information on operational, under-construction, and planned CSP projects worldwide. No proprietary or restricted datasets were used in this study.

Author contributions

- Brenda Hernandez Corona: Writing – original draft, Investigation, Visualization
- Dr. Matteo Chiesa: Funding acquisition, Resources, Writing – review & editing
- Dr. Ahmad Mayyas: Resources. Supervision. Writing – review & editing
- Dr. Nicolas Lopez Ferber: Methodology, Writing – review & editing
- Dr. Nicolas Calvet: Conceptualization, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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