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SUSTAINABLE AND RENEWABLE ENERGY (SE HOSSEINI, SECTION EDITOR)

# Concentrating Solar Power (CSP)—Thermal Energy Storage (TES) Advanced Concept Development and Demonstrations

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## Abstract

**Purpose of Review** This paper highlights recent developments in utility scale concentrating solar power (CSP) central receiver, heat transfer fluid, and thermal energy storage (TES) research. The purpose of this review is to highlight alternative designs and system architectures, emphasizing approaches which differentiate themselves from conventional solutions.

**Recent Findings** The push for increased efficiency and compatibility with high-temperature power cycles has driven the development of advanced receiver concepts utilizing various heat collecting media. Published work can be grouped into three technologies like US Department of Energy Gen3 CSP pathways: liquid, gas, and solid receivers, each with TES approaches ideally suited for system integration. Most experimental work has focused on material property investigation, with few system-level validations at meaningful scales.

**Summary** Innovative solutions utilizing advances in design, materials, and manufacturing are being pursued to realize advanced CSP-TES systems. Of those concepts built and tested, demonstrations have shown promise and remain topics of active development. With continued development, these systems can offer alternative pathways towards low-cost, dispatchable electricity production.

**Keywords** Concentrating solar power (CSP) · Thermal energy storage (TES) · Power tower · Central receiver · Demonstration · Dispatchability

**Abbreviations**

| | |
|---|---|
| CSP | concentrating solar power |
| DNI | direct normal irradiance |
| HCM | heat collecting media |
| HTF | heat transfer fluid |
| LCOE | levelized cost of energy |
| PCM | phase change material |
| $sCO_2$ | supercritical carbon dioxide |
| TES | thermal energy storage |

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## Introduction

Concentrating solar power (CSP) remains an attractive component of the future electric generation mix. CSP plants with thermal energy storage (TES) can overcome the intermittency of solar and other renewables, enabling dispatchable power production independent of fossil fuels and associated $CO_2$ emissions.

Worldwide, much has been done over the past several decades to develop and validate what are now viewed as “conventional” CSP-TES solutions. Current state of the art commercial CSP-TES utilizes a central receiver, or power tower, layout—typically with molten nitrate salt serving as both the heat transfer fluid (HTF) and TES media, stored in a two-tank configuration and coupled to a steam turbine.

As solar photovoltaics continue to decline in price, the push for reduced CSP costs has stimulated urgency to reduce CSP-TES levelized cost of energy (LCOE) and increase value to the grid. Reduction in costs can be accomplished by increasing the operational lifetime of the system, installing in a sunnier locale, decreasing complexity and capital costs, or increasing system efficiency. Compatibility with efficient high-temperature power cycles has driven the development of advanced CSP receiver concepts utilizing various HTF, and associated TES systems. Several competing architectures are being pursued: liquid, solid, and gas HTF designs, many with surface absorption-conduction and volumetric variants.

## CSP Receivers

### Liquid Receivers

In tubular liquid receivers, a set of tubes absorb incoming solar radiation and transfer this energy to HTF circulating inside. The peak flux and working temperatures are therefore limited by the material properties of the absorber tubes. This design is considered conventional for commercial molten salt CSP plants; ongoing work is focused on optimizing operational conditions, (re)designing for higher temperatures, working pressures and aggressive HTF, and improving optical performance. For example, Fritsch et al. developed simplified FEM models to study the heat transfer behavior of central receivers subjected to a transient inhomogeneous flux distribution [1]. These models can be used to compare various receiver designs. In case of molten salts, it was noted that the emissivity of tube-coatings had a less significant effect on thermal efficiency than its absorptivity [2]. Additional studies show that selective receiver coatings (absorptance $\geq 0.95$, thermal emittance $\leq 0.6$) reduce LCOE; in ideal cases a 12% reduction in plant LCOE can be attributed to coating performance and maintenance [3].

Direct volumetric absorption can eliminate tube-based receiver restrictions [4]. In these concepts, concentrated sunlight is directed into a semi-transparent medium, typically contained in a well-insulated, open top deep receiver. Liquid surfaces are self-healing and can withstand high fluxes; hence, high working temperatures can be achieved. In particular, Casati et al. developed a molten silicate glass receiver that reached 1300 °C at fluxes up to 1.2 MW/m$^2$ [5]. An inverted temperature profile is obtained such that the peak temperature is located within the bulk of the fluid rather than at the surface, which in turn reduces the radiative losses from the top surface. However, as the size of the system increases, radiative losses from the liquid free surface also increase. Tetreault-Friend et al. demonstrated that by utilizing hollow fused silica spheres, a floating structure that can be scaled to any size, thermal losses can be reduced by 51% [6]. Grange et al. reported a conical final concentrator to further concentrate input flux, while also reducing contamination and convection losses [7]. On the same 100-kW demonstration system, an origami-based mixing element was designed to circumvent the generation of thermal gradients in salt [8]. Using origami methodology, an old Japanese paper-folding art, a large three-dimensional mixing element was constructed from two-dimensional metal sheets. This allowed on-site assembly within the volumetric receiver and reduced shipping and manufacturing costs significantly. Interestingly, thermal gradients can give rise to natural convection cells within the receiving media and provide efficient mixing. Therefore, more work is needed to better understand the behavior of natural convection and temperature profiles in such situations.

Alternatively, thin-films can absorb the incoming radiation [9••]. Like open volumetric receivers, exposed films are prone to contamination and wind may influence fluid flow and heat transfer. Internal direct absorption receivers can be utilized to counter these challenges and potentially reduce LCOE by 8% [10]. Herrera et al. modeled gravity driven flow of molten glass thin-films (3 mm) over an inclined plate, noting the film thickness and heat transfer decreased by 50% due to temperature-driven viscosity changes of the glass [11]. Nanoparticles can be added to HTF films to enhance solar absorption. However, high particle concentrations may increase pumping power, and optical properties of the nanoparticles vary spectrally with their morphology. A blended plasmonic nanofluid can be fine-tuned to achieve high solar absorptivity [12], whereby a lower concentration is sufficient to absorb solar energy, reducing pumping loads [13]. Nevertheless, for a fixed film thickness, increasing the absorption coefficient beyond a certain limit does not improve collector efficiency [14].

### Liquid HTF

Nitrate salts are the most common HTF due to low corrosion rates (2 μm/year on SS321) and melting temperatures (220 °C) [15]. They have high heat capacities (~ 1.5 kJ kg$^{-1}$ K$^{-1}$) and low costs (0.5 $/kg), but decompose at relatively lower temperatures (~ 600 °C) [15, 16•]. Additionally, optical properties are negatively affected by decomposition [16•]. Adding $LiNO_3$ or $Ca(NO_3)_2$ to Hitec salt: $NaNO_3/KNO_3/NaNO_2$ (7/53/40 wt%) can result in improved thermal stability [16•, 17]. Xu et al. developed lithium-based quaternary nitrate salts having a wide operating temperature range (95–450 °C) [17]. In another study, $LiNO_3$-based salts exhibited better thermal stability in the presence of $O_2$ [18]. Likewise, the presence of $LiNO_3$ improves corrosion resistance; however, the cost associated with lithium salts is very high, with the cost of salt cations stated as $Ca < Na < K < Li$ [19]. In contrast, Montane concluded that using $LiNO_3$ salts can result in low LCOE as they possess high-energy storage densities [20].

Carbonate salts offer high thermal stability (800–850 °C) and heat capacity (~ 1.5 kJ kg$^{-1}$ K$^{-1}$) [15, 21]. High costs, corrosion rates (~ 1000 μm/year for Inconel 600) and melting temperatures (~ 400 °C) hinder practical application [15]. Thermo-physical properties of binary carbonates can be controlled by changing relative compositions of lithium and potassium [22]. Ternary carbonates typically have lower melting temperatures than binary carbonates; adding LiOH/KOH mixtures to ternary carbonates reduces the melting temperature [23]. Similarly, the addition of LiF to LiNaK carbonates reduces melting point (386 °C) [24]. Cr/Ni-rich austenitic stainless steel grades have lower corrosion rates in carbonate salts [25]; Inconel 718 and alumina-forming austenitic alloys can be utilized to circumvent fast corrosion [26, 27].

Chloride salt mixtures possess high thermal stability (> 800 °C), moderate heat capacity (~ 1.0 kJ $kg^{-1}$ $K^{-1}$) and are very inexpensive (< 0.5 $/kg) [15]. Only minor variations are observed in their thermo-physical properties over a wide range of operating temperatures [28–30]. Xu et al. theoretically compared various molten salts and concluded that the highest Carnot efficiencies were achieved using chloride salt mixtures [31]. Similarly, Tetreault-Friend et al. noted that optical properties of chloride salts remained relatively constant even at 800 °C [16•]. However, chloride salts are highly corrosive to metals (> 300 μm/year on SS304), severely damaging the structural material of typical receivers [15]. Vignarooban et al. demonstrated that Hastelloys perform better (< 10 μm/year) in the presence of anaerobic ternary chloride salt mixtures [32]. Electrolysis techniques are reported to remove corrosive hydroxide species from the salt [33]. Likewise, amorphous metal coatings can provide corrosion resistance [34]. Dutta suggested using lithium based mixtures as it helps in formation of protective perovskite crystals on steel surfaces [35]. Corrosion models can be employed to theoretically predict corrosion rates [36], and low thermal conductivity and heat capacity (< 1 W/m K) can be compensated using Zn particles [37].

Fluoride salts can offer high thermal stability at temperatures above 700 °C, along with high heat storage capacity (1.9 kJ $kg^{-1}$ $K^{-1}$) [9••, 15]. In particular, FLiBe salt has been studied extensively as a coolant and solvent for fissile material in nuclear reactor applications [38]. However, limited research investigating their implementation in CSP applications is available, reportedly due to their high costs (2–7.8 $/kg), high melting temperatures (454 °C), and environmental hazards [15, 36, 38]. As an alternative, small quantities of fluoride salts can be mixed as additives to other salts to enhance their properties at lower cost [24]. Andreades et al. have suggested utilizing molten fluoride salts to couple CSP and nuclear heat sources for adapting open-air Brayton power cycles [39].

Liquid metals possess high thermal conductivity (63 W/m K) and stability (> 1000 °C), low viscosity (0.16 mPa s), and low melting point (29.8 °C) [40, 41]. However, one of the main challenges is corrosiveness towards metal alloys. Liquid metals are compatible with refractory materials, therefore Amy et al. have proposed using ceramic liquid pumps [42, 43]. They demonstrated that liquid tin can be pumped effectively at temperatures as high as 1400 °C. Nevertheless, ceramic pumps have much higher manufacturing costs than traditional metal pumps. Liquid metals also have higher costs (up to 450 $/kg) [40], but due to their high thermal conductivities, liquid metals need smaller absorber area and can tolerate higher fluxes (3.0 $MW/m^2$), reducing LCOE by 16% [44, 45]. Liquid metals such as lead-bismuth and sodium have a poor thermal storage capacity [21, 46]. Conroy et al. concluded that liquid sodium is cost-effective only for low storage (< 3 h) systems [44]. Additionally, a single tank thermocline storage is recommended for liquid-sodium [47]. Jaeger developed Nusselt-number correlations for liquid metals flowing through ducts of various geometries which can be used to further investigate heat transfer efficiencies [48]. Several research teams and startups are advancing high-temperature sodium receiver designs from lab scale to demonstration systems, including Vast Solar's 6 MW modular pilot plant [49–51].

## Gas Receivers

Pressurized gases such as air and supercritical carbon dioxide ($sCO_2$) have been examined to feed Brayton cycle heat engines; the working principle for gas tubular receivers is the same as liquid HTF tubular receivers [52]. For small-scale applications, multi-cavity tubular receivers can outperform volumetric receivers [53]. Nithyanandam et al. suggested using smaller diameter tubes to achieve high thermal efficiencies and durability [54]. However, high solar flux and low mass flowrates are required to compensate for greater pressure drops. Pressurized air in spiral double conical tubes achieved high outlet temperatures (908 °C) at relatively low direct normal irradiance (DNI) [55]. Ortega et al. concluded that more gas recirculation results in higher thermal efficiencies [56]. Likewise, finned receiver structures can be utilized to induce a light trapping effect and reduce re-radiation to the environment [57].

In volumetric air receivers, solar radiation is absorbed volumetrically by a porous solid structure, which in turn heats gases directed through the structure; these can sustain high flux and temperatures above 800 °C can be achieved. Nonetheless, high solar fluxes are required throughout the year to maintain high gas turbine inlet temperatures [58]. High receiver cellularity, thermal conductivity, and porosity of the absorber are required for high efficiency; for ceramic foams, it was noted that absorber efficiency is influenced by the first layer only and additional layers are not advantageous [59]. Pabst et al. modified straight 1D honeycomb absorber geometry using an iron-based alloy to achieve up to 80% efficiency [60]. Cagnoli et al. developed a multi-scale model to investigate the effects of non-uniform flux distributions, return air flow, and cloud covers on absorber performance [61]. They concluded that in the absence of any control strategy, receiver front face temperature becomes highly sensitive to flux variations and drops rapidly when there is no flux.

Small particle receivers can be used for direct volumetric absorption and directionally stratified heating in otherwise optically transparent fluids. In such systems, the gas flow is seeded with particles which strongly absorb the incoming solar flux; the particles transfer this absorbed energy to the gas. Nevertheless, the effective heat transfer coefficient between the particles and the gas can be reduced up to 25% due to turbulence-induced inhomogeneous concentrations [62]. Fernandez and Miller suggested receiver modifications, such as use of aluminum oxide walls and a 45° spherical-cap window, to achieve modeled efficiencies up to 90% [63].

## Gas HTF

Air is abundant and can even be utilized directly as HTF in non-pressurized form. Additionally, it is stable at high temperatures, achieving high thermodynamic efficiencies. However, high mass flowrates are required due to poor heat transfer properties, resulting in large parasitic pumping power losses, pushing the operational range of industrial turbomachinery in order to achieve high efficiencies [64]. Similarly, $sCO_2$ is a non-toxic gas with high power conversion efficiency and thermal stability ($>650$ °C) [54]. Smaller turbomachinery is required owing to its high power density, resulting in low heat losses and mass flowrates [56]. Very high working pressures (25 MPa) and temperatures make the system prone to structural failures [54].

Alternatively, air-nanoparticle mixtures can be employed, but particles must be separated before air enters the turbine. Alternatively, carbon nanoparticles oxidize during the absorption process and therefore separation is not required [63]. Reportedly, optical properties of metal-oxide nanoparticles remain constant between 25 and 500 °C; potentially presenting a new class of gas-based HTF [65]. Gas HTF systems typically require the use of a secondary storage media for thermal energy storage—however, hybridized CSP-gas turbine systems are attractive in certain areas with fossil fuel used for nighttime backup [66].

## Solid Receivers

In a falling particle receiver, small inert particles fall from a slot at the top of a cavity and serve as the solar collecting media. Temperatures up to 1000 °C can be achieved; solid particles can store thermal energy in sensible form hence the system has an inherent storage capability [67–69]. However, such high temperatures with particle-wall interactions require refractory lined receiver wall construction [70]. Particle containment, conveyance and flow, debris filtration, and heat loss present challenges for implementation, but research groups are actively addressing these risks. Wire meshes can be employed as both filters and obstructions, to capture debris and increase residence time, respectively, but require careful designing as meshes can obstruct flow [70]. Yue et al. suggested quartz-shells as an aperture cover to reduce heat losses, but the cover resulted in a lower thermal efficiency [71]. Stability of the particle curtain is important; opacity depends on slot aperture and distance from the release point [67], and opacity control influences receiver efficiency. Higher opacity can be obtained by recirculating the particles [72], but the receiver cost is expected to increase by 65 $\$/kW_t$ in such a case [73]. A stationary porous or porcupine structure can be used as an obstruction to increase particle residence time, thus enabling higher temperatures in a single pass [68, 74, 75]. Similarly, a rotary kiln utilizing centrifugal force can control particle speed [76]. To compensate for the low solar absorptance of the particle curtain, an indirect absorption approach decouples solar absorptance from particle heat carrying capacity, widening the range of particles that can be utilized. One such approach utilizes an array of absorber tubes whereby falling particles absorb the energy indirectly from these tubes [77].

In fluidized receivers, air flows over irradiated solid particles in transparent tubes without solid circulation [78]. This strategy reduces particle contamination or loss at the expense of containment tube reflection and absorption losses. Reportedly, temperatures up to 624 °C (multiple tube array) and 867 °C (single tube) can be reached [76, 79]. Zhang et al. studied fluidized heat transport inside metal and quartz tubes and concluded that quartz tubes provide better heat absorption [80]. For quartz tubes, higher air mass flowrate resulted in higher fluidized particle outlet temperatures, while the opposite occurred in the case of metal tubes. Indirect absorption is also possible by forcing the solid particles upwards, using an airflow through irradiated tubes [78]. These receivers use a large solid fraction and a low gas velocity. For a solid mass flux of 45 $kg/m^2$-s, the heat transfer coefficient from wall to mixture was evaluated to be 1100 $W/m^2$ K [81]. However, additional power is required to suspend particles and maintaining a constant mass flowrate currently presents challenges.

## Solid Heat Collecting Media

For solid receiver applications, particles should resist agglomeration and sintering, and have high solar absorptivity, packing density, and heat capacity [70]. Ho et al. conducted various studies on candidate materials and concluded that Accucast ID50 (a black colored ceramic) demonstrated the best performance [70]. Diago et al. noted that desert sand can absorb solar radiation directly and remains thermally stable up to 1000 °C [82]; Al-Ansary et al. demonstrated a falling particle receiver using Saudi Arabian red sand as the heat collecting media (HCM) [83••]. Although sand presents a near zero-cost alternative, excessive calcium carbonate content can cause undesirable particle agglomeration. Therefore, sand collection points must be selected carefully. Ferromagnetic particles, controlled by magnetic fields, were reported to mitigate wind-induced flow disturbances and reduce the falling speed of particles [69]. Similarly, silicon carbide, zirconia and chamotte were promising [84]. Solid HCM offers a direct path to high-temperature thermal storage—with existing fluidized bed technology directly applicable to particle heat extraction and coupling to power cycles [85]. Nevertheless, detailed studies on optical-thermal-tribology properties of many candidates remain unavailable in the literature.

## Emerging Technologies on TES Systems

### Concrete and Ceramic Storage: Eco Tech Ceram and Energy Nest

From 2003 to 2006 DLR tested ceramic and high-temperature concrete TES prototypes in Plataforma Solar de Almeria (PSA), Spain [86]. This established a baseline for using low-cost castable sensible heat storage materials; the prototype shell-and-tube heat exchanger utilized the castable as fill between the shell and the tubes.

One drawback of concrete as TES material is the different dilation ratio as compared with steel piping. Over time, this difference can lead to cracking, spallation, and a loss of contact between the concrete and the pipe, creating a small air gap which decreases the heat transfer coefficient. To overcome this problem, two main strategies have been investigated: (1) direct contact between HTF and TES media (i.e., no pipe liner) and (2) matched coefficient of thermal expansion concrete.

To achieve direct contact between the HTF and TES media, ceramic materials were obtained from industrial wastes containing asbestos (e.g., Cofalit®) and more recently from the mixture of municipal waste incinerator ashes and clays [87]. This trend using waste and cost-effective materials has led to the design of modular thermal batteries using standard shipping containers, tested and commercialized by Eco Tech Ceram. The EcoStock device consists of a 3-MWh capacity air/ceramic system able to operate at high temperature (up to 900 °C), which is arranged as a horizontal thermocline fitted into a standard 20-ft. container. Lopez Ferber et al. examined an experimental packed bed pilot at small but representative scale: 45 kWh of storage capacity at 600 °C [88]. They reported that the horizontal thermocline presents some disadvantages compared with the vertical one, but the increased contact area with the ground implies minimal structural load on the system. Moreover, the horizontal configuration may also help to reduce thermal ratcheting.

The alternate strategy consists of a modified concrete mixture with a thermal expansion coefficient like the heat exchanger ferrous metal piping. This approach has been adopted by Nest Energy, testing 2 × 500-kWh prototypes with a new solid state concrete-like storage medium, denoted HEATCRETE® vp1 with cast-in steel piping. The system was tested at the Masdar Institute Solar Platform for more than 20 months, accumulating 6000 operational hours and completing 279 charge/discharge cycles up to 380 °C, and demonstrated its viability at commercial scale [89•]. It was destructively evaluated after testing and showed no sign of damage or piping-TES media separation, warranting adoption in pilot plants.

### Packed Bed: Low-Cost Sensible Heat/Solid Materials

Packed bed TES consists of a single tank thermocline filled with a solid material in order to minimize mixing of the hot and cold volumes of liquid HTF; additionally, the solid filler can store the same order of magnitude of energy as the HTF. Moreover, addition of filler materials reduces system costs and allows better control of tank stratification the outlet temperature during discharging [90]. Bed materials can consist of solids, such as rocks, ceramics, or even waste materials like metal slags. Tank stratification is promoted during charging by circulating HTF through the voids in the bed from top to bottom, while during discharging it circulates from bottom to top.

Major challenges in the design and operation of packed beds include (1) non-uniform flow distribution in the tank, which may lead to non-homogenous tank temperature on charging and consequently to loss of storage capacity; (2) the potential lack of stability of the filler material in the hot fluid (molten salt or oil) environment, which can cause problems of corrosion/degradation of the filler and HTF, and increased pressure drop; and (3) thermo-mechanically induced ratcheting, produced by the expansion and contraction of the filler, and which can mechanically rupture the tank.

Zanganeh et al. [91] presented a model of a packed bed pilot plant demonstration consisting of a 2-m high truncated cone shaped tank, which decreases from ⌀2 m on top to ⌀1.25 m on bottom, in order to maximize the hot volume of the tank and increase the system capacity. The tank was buried in the ground, utilizing a 15-mm layer of ultra-high performance concrete on the packed bed side for high mechanical stability, surrounded by a 235-mm layer of low density, low thermal conductivity concrete in order to reduce thermal losses. Concrete fabrication was used to avoid thermal ratcheting effect, and rocks with a 2–3-cm diameter were used as filler, with air as HTF.

## Fluidized Bed: Low-Cost TES Materials

Fluidized beds have extensive history in industrial processes promoting high levels of contact between gases and solids, enabling good heat transfer, and allowing the bed to maintain a homogeneous temperature field. The recent development of suitable solar particle receivers has renewed interest in fluidized bed TES applications.

Typically, a system based on this technology integrates the particle receiver with the TES and the power block. The particles heated in the receiver are then transported to the TES system, which consists of one or more hot and cold particle storage silos. The hot particles are dispatched to the heat exchanger where energy is transferred from the hot solids to a secondary HTF (typically air or another type of gas) which will transfer the heat in a second heat exchanger (gas/steam) to operate the turbine and produce electricity. After energy has been extracted from the particles, particles are returned to the cold particle storage silo; cold particles are conveyed back to the receiver, with a bucket elevator or alternate solids conveying system, when solar flux is available for a subsequent cycle of heat absorption.

The use of solid particles as the HCM helps overcome some of the operational difficulties posed by molten salt-based systems, mainly the suppression of HTF freezing risks [92]. Moreover, the most important advantage is the use of a high-temperature gas HTF from particles to power block enabling direct implementation of Brayton power cycles with higher efficiency. Sandia National Laboratories has prototyped a 1-MW design, with an obstructed flow receiver variant installed in Saudi Arabia, representing larger scale demonstrations of falling particle receivers [83••, 93, 94].

Another recent example of fluidized bed TES is the STEM® (Solar Thermo Electric Magaldi) CSP plant in San Filippo del Mela, Sicily (Italy) [95]. The plant, a modular unit of 2 MW able to store up to 8.2 MWh, started operation June 2016 and represents a breakthrough as the first commercial unit sand TES.

**Table 1** Summary of CSP receiver and HTF experimental and theoretical papers cited

| Research area | Experimental papers | References | Theoretical papers | References | E/T |
|---|---|---|---|---|---|
| Liquid receivers | | | | | |
| Tubular | 0 | | 2 | [1, 2] | 0/2 |
| Volumetric | 2 | [5, 6] | 4 | [4, 6–8] | 2/4 |
| Surface | 0 | | 4 | [10, 11, 12, 14] | 0/4 |
| Liquid HTF | | | | | |
| Nitrate salts | 5 | [15–19] | 3 | [17, 20, 31] | 5/3 |
| Carbonate salts | 6 | [22–27] | 1 | [31] | 6/1 |
| Chloride salts | 8 | [16•, 29, 30, 32–35, 37] | 3 | [15, 31,36] | 8/3 |
| Fluoride salts | 1 | [24] | 1 | [38, 39] | 1/1 |
| Liquid metals | 2 | [42, 43] | 5 | [44–48] | 2/5 |
| Gas receivers | | | | | |
| Tubular | 1 | [55] | 5 | [53–57] | 1/5 |
| Volumetric | 2 | [59, 60] | 3 | [58–61] | 2/3 |
| Small particles | 0 | | 2 | [62, 63] | 0/2 |
| Gas HTF | | | | | |
| Air | 0 | | 1 | [64] | 0/1 |
| $sCO_2$ | 0 | | 2 | [54, 56] | 0/2 |
| Air-nanoparticles | 1 | [65] | 1 | [63] | 1/1 |
| Solid receivers | | | | | |
| Falling particles | 2 | [74, 75] | 8 | [67–69, 71–74, 77] | 2/8 |
| Fluidized | 2 | [79, 80] | 2 | [78, 80] | 2/2 |
| Solid HCM | | | | | |
| Particles | 1 | [82] | 1 | [69] | 1/1 |
| Total | | | | | |
| | 33 | | 43 | | 33/43 |

## Integrated receiver + TES: Concentrated solar power on demand (CSPonD) demonstration

The CSPonD collocated volumetric salt receiver and thermocline TES concept diverges from conventional CSP technologies and aims to overcome inherent system limitations like electric heat tracing and HTF pumping parasitic losses, as well as reducing the liabilities of salt freezing. Concentrated light is sent directly to the molten salt storage tank, which combines the function of TES system and volumetric receiver [4, 7, 8]. This concept pairs well with beam down heliostat field architectures, which utilize a second reflection of the solar beam from the heliostats field to the receiver. Even considering increased optical losses, the advantages of the concept still make it extremely attractive: reduction of the number of storage tanks and piping, simplifying startup and daily operation.

The project, shared by Masdar and MIT, successfully built and tested a 600-kWh CSPonD storage tank at Masdar's Beam Down Optical Experiment from 2014 to 2017 [96••]. The prototype demonstrated feasibility of the concept complete with controllable assisted thermocline divider and mixing plates; also critical were demonstrations that proved initial salt melting and recovery from a solid system freeze could be accomplished in situ using the energy from the solar field. Several challenges remain for larger installations, but the system is promising for modular field designs; the 15-module Yumen Xinneng 50 $MW_e$ beam-down plant provides a relevant benchmark for commercial feasibility.

## PCM-Based Systems

Another concept uses a screw heat exchanger to transport phase change material (PCM) from a cold to a hot tank or vice versa during phase change, developed at Fraunhofer ISE [97]. This separates the size of the heat transfer area and the storage capacity, while existing concepts based on static PCM do not have this ability. The system was conceived for CSP direct steam generation production at 110 bar and 520 °C, using $NaNO_3$ as PCM.

The PCM selected for the laboratory scale prototype was the eutectic mixture of $NaNO_3$ and $KNO_3$ with a melting point at 221 °C. It can be molten during charging with steam at a pressure of 28 bar and temperature of 231 °C. The screw heat exchanger transports the PCM along the heat exchanger area during phase change; charging steam/discharging water flows through a hollow shaft, screws, and trough, and one screw is utilized for both charging and discharging. The storage material is stored in two separate tanks, one for molten PCM and another one for solid PCM. With this novel two-tank concept, the size of the heat transfer area, and the storage capacity are decoupled, and it is possible to develop an economically viable latent storage. An analysis of LCOE was performed also by Zipf et al. [98] considering screw PCM storage in a 50 $MW_e$ plant. In general, this innovative concept has potential to compete with existing thermal storage technologies, decreasing storage cost by 20% and LCOE by 5%, pending further optimization.

Another relevant and recent PCM development was carried out by Rodriguez-Aseguinolaza et al. [99], who identified the eutectic $Mg_{49}$-$Zn_{51}$ as potential material and studied its thermophysical properties in order to determine the suitability of this alloy as large TES material. The authors concluded the

**Fig. 1** Representative CSP-TES demonstrations, from top: KSA Red Sand Falling Particle Receiver/TES Riyadh, Saudi Arabia [83••]; STEM CSP Fluidized Bed Receiver/Sand TES, San Filippo del Mela, Sicily, Italy [95]; Masdar-MIT CSPonD Volumetric Salt Receiver/TES, Abu Dhabi, UAE [96••]

main advantages of $Mg_{49}Zn_{51}$ are high thermal diffusivity, heat capacity, and energy density compared with molten salts.

Risueno et al. [100] extended the study of metal alloys as PCMs analyzing the thermophysical properties of two ternary eutectic alloys: $Mg_{70}$-$Zn_{24.9}$-$Al_{5.1}$ and $Zn_{85.8}$-$Al_{8.2}$-$Mg_6$. The thermal performance of these materials after 700 cycles was examined, along with chemical compatibility tests with 304, 304 L, 316, and 316 L stainless steels. The results confirmed these types of alloys are suitable for TES applications.

The Mg-Zn eutectic metal alloy was posteriorly tested in a laboratory scale TES unit by Blanco et al. [101]. The TES unit consisted on two concentric tubes, with the central tube surrounded by 67 kg of alloy and a central tube through which liquid HTF flows. The results corroborate PCMs with high thermal conductivity, such as eutectic metal alloys, are suitable for direct steam generation applications due to the quasi-constant melting and solidification temperatures and high heat transfer capacity and thermal conductivity. However, questions remain as to the technoeconomic viability of this solution at larger scale.

## Conclusions

CSP receiver developments can be grouped by heat collection media and fundamental operating mechanisms. Recent work is driven by compatibility goals with high-temperature power cycles and improved system efficiency targets, aligned with US Department of Energy Gen3 CSP pathways [102•]. Of the work highlighted in this paper, a majority was theoretical; most of the experimental work focused on the investigation of material properties only (Table 1). In addition, very few experimental studies on proposed receiver designs or modifications are available. This is to be expected, as only a handful of CSP experimental platforms are scattered worldwide and prototype costs can be high for meaningful-scale testing. In order to speed development of practical solutions, targeted experimental validation of models is needed.

Similarly, innovative designs and materials have been reported in advanced TES development. Notably, larger demonstrations have shown validity of advanced direct absorption receiver concepts, integrated with TES (Fig. 1). This is promising for future research and commercialization efforts, as each step up in system size and demonstration increases the visibility and bankability of that concept, as well as the entire CSP-TES technology landscape. Several key technical challenges remain: understanding HTF/heat collecting media/TES structure decades-long term degradation, management of system losses and utilization, and optimal operation and maintenance schemes. However, the development of modular CSP and TES solutions are reducing the economic and technical barriers inherent in multiple orders-of-magnitude system scaling from concept-level testing to final commercialization.

## Compliance with Ethical Standards

**Human and Animal Rights** This article does not contain any studies with human or animal subjects performed by any of the authors.

## References

Papers of particular interest, published recently, have been highlighted as:

- Of importance

•• Of major importance

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