

Safety of Thermal Energy Storage Systems for Concentrating Solar Power Plants

Clifford K. Ho

Sandia National Laboratories
Concentrating Solar Technologies Dept.
Albuquerque, New Mexico
ckho@sandia.gov, (505) 844-2384

SAND2017-1795 C



Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

*Exceptional service
in the national interest*

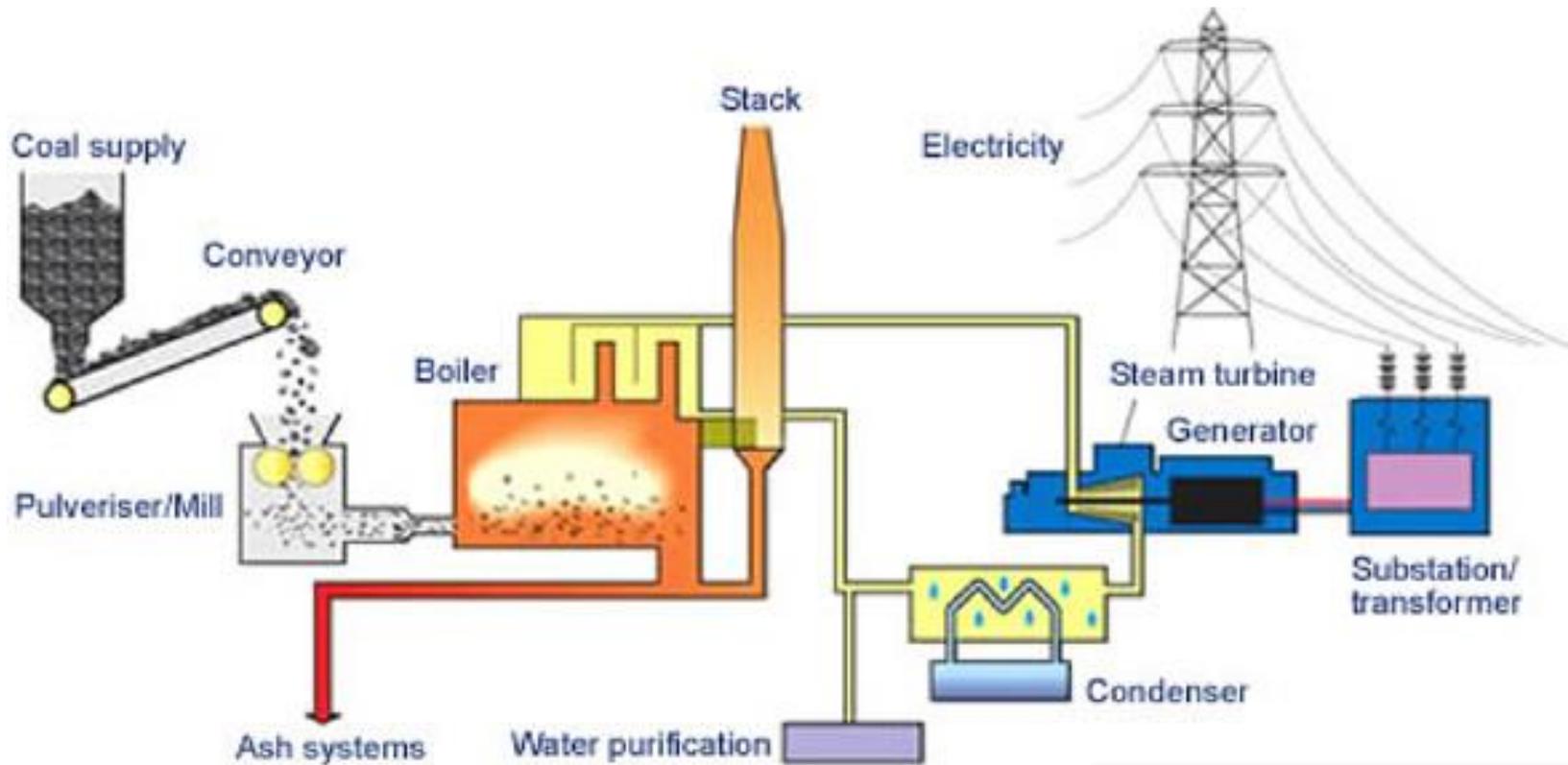


Outline

- Introduction to CSP and Thermal Storage
- Commercial CSP Plants with Thermal Storage
- Safety Issues

What is Concentrating Solar Power (CSP)?

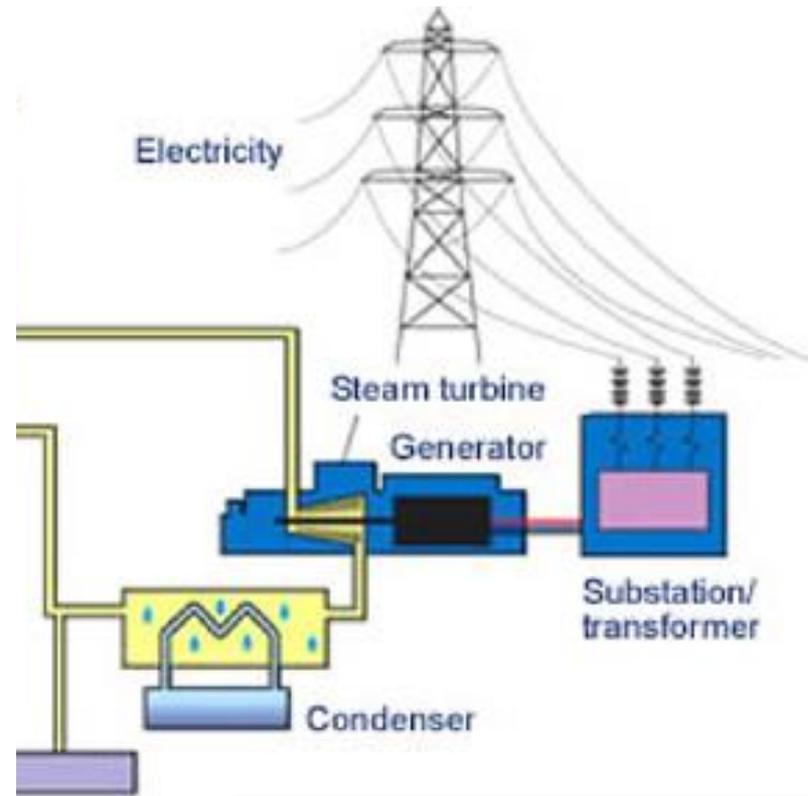
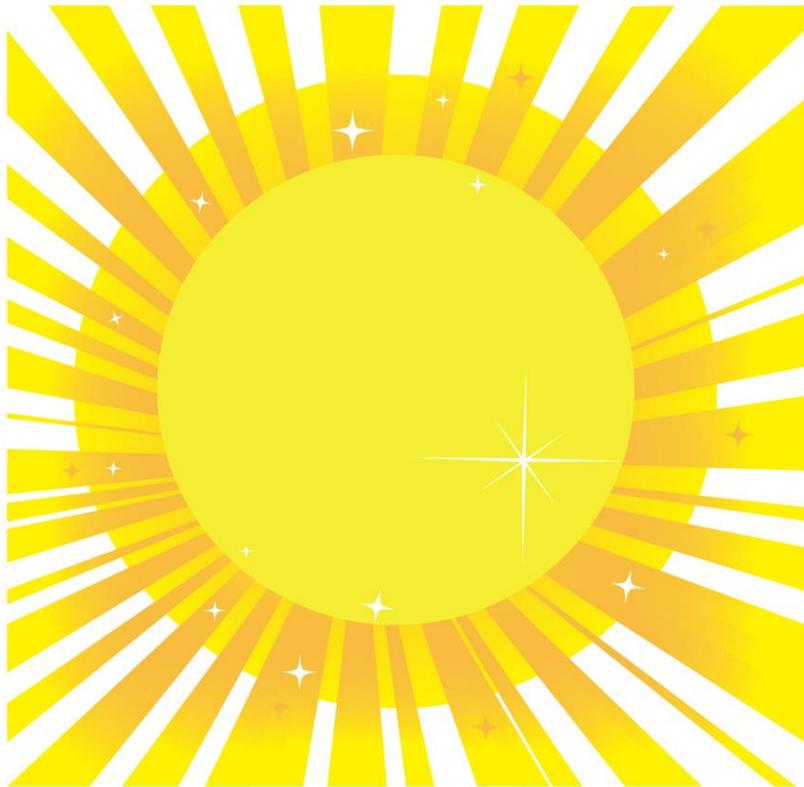
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle



Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)? Sandia National Laboratories

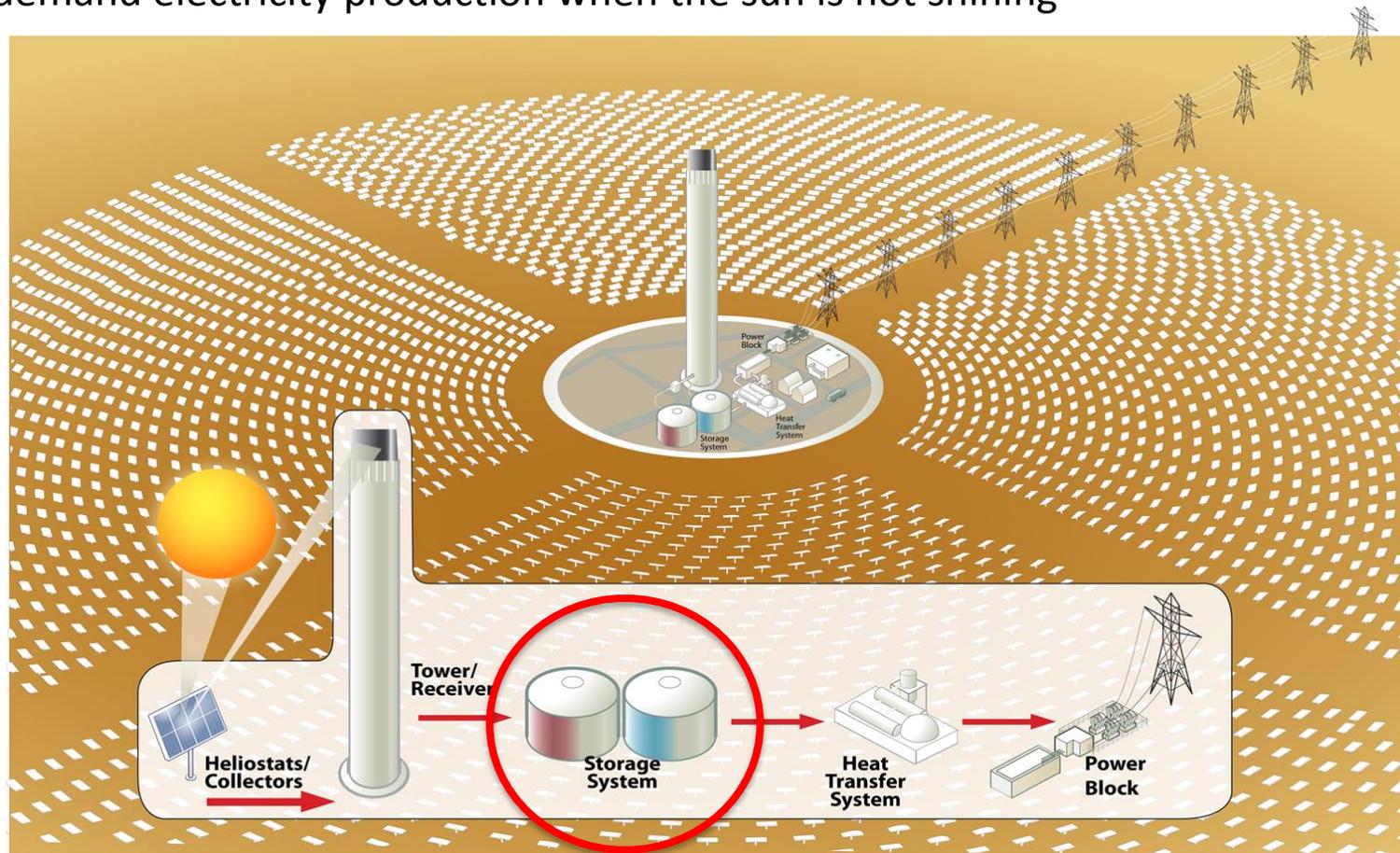
CSP uses concentrated heat from the sun as an alternative heat source for the power cycle



Concentrating Solar Power

CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



Types of Thermal Energy Storage

- Sensible (single-phase) storage
 - Use temperature difference to store heat
 - Molten salts (nitrates <600 C; carbonates, chlorides 700 – 900 C)
 - Solids storage (graphite, concrete, ceramic particles), >1000 C
- Phase-change materials
 - Use latent heat to store energy (e.g., molten salts, metallic alloys)
- Thermochemical storage
 - Converting solar energy into chemical bonds to store energy (e.g., decomposition/synthesis, redox reactions)



Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa



Falling particles for direct solar heating

Outline

- Introduction to CSP and Thermal Storage
- Commercial CSP Plants with Thermal Storage
- Safety Issues

Gemasolar

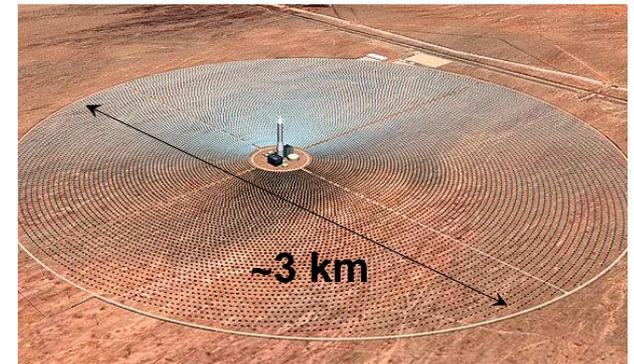
(near Seville, Spain)



- 1st commercial power tower (19 MW) in the world with 24/7 dispatchable energy production (15 hours of thermal storage using molten salt heated from ~300 – 600 C; ~300 MWh). Commissioned in May 2011.

Crescent Dunes

Tonopah, Nevada



110 MWe power tower near Tonopah, NV. 10 hours of thermal storage (1.1 GWh) using molten nitrate salt heated from $\sim 300 - 600$ Commissioned in 2015.

Solana Generating Station



280 MW parabolic trough plant
Phoenix, AZ (Gila Bend)
Started 2013



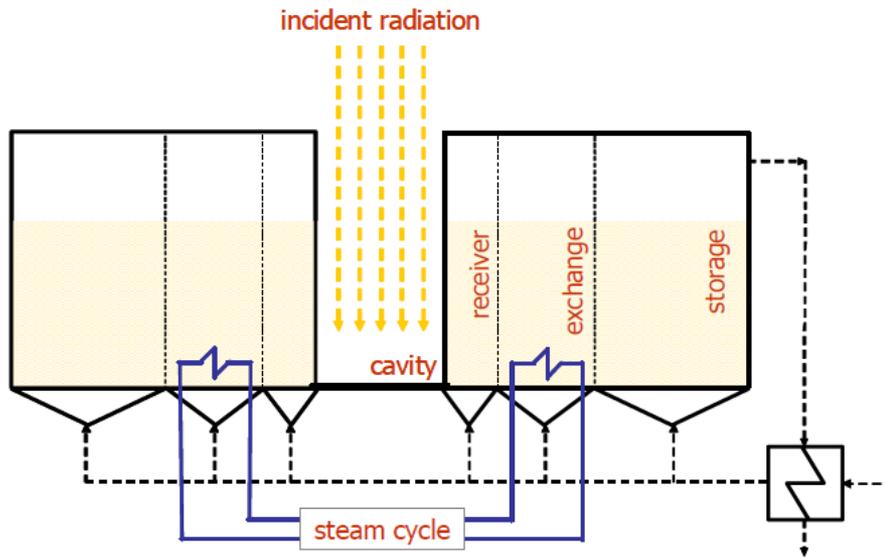
futureenergyweb.es



6 hours of molten-salt storage
heated from $\sim 300 - 400$ C
(1.7 GWh)

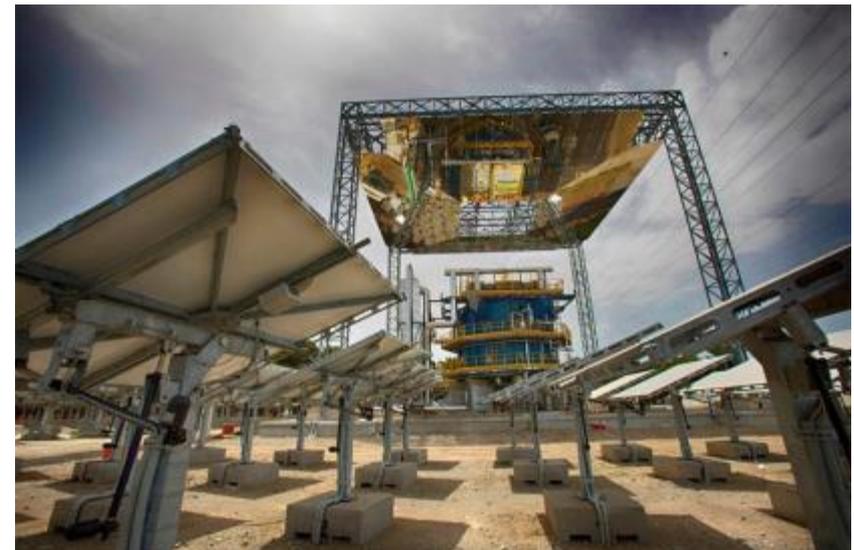
2 MW_t Fluidized-Bed Power Plant – Sicily, Italy

Magaldi Group



- 2 MW_t modular beam-down fluidized-bed receiver units
- Superheated steam at 520 C
- 6 hours thermal storage

Chirone et al. 2013



Solid-based (graphite) central-receiver system at Lake Cargelligo, NSW, Australia

- Graphite block is heated in face-down receiver
- Used to heat steam from 200 C to 500 C
 - Powers a 3 MW_e steam-Rankine cycle.



Outline

- Introduction to CSP and Thermal Storage
- Commercial CSP Plants with Thermal Storage
- Safety Issues

Molten Salt Use in Industry

- Molten salt baths have been used in industry for metal treatment for over a century
 - Molten nitrate (200 – 550 C)
 - Molten cyanide (800 – 950 C)
 - Molten chloride (700 C – 1,100 C)
- Well-established safety protocols used in industry
 - Storage
 - Operation / Maintenance
 - Protective clothing and equipment
 - Disposal



Thermal Storage Safety for CSP

- National Fire Protection Agency classifies solar salts (60% sodium nitrate, 40% potassium nitrate) as Class I oxidizers
 - Least hazardous of four classes
 - “an oxidizing material whose primary hazard is that it may increase the burning rate of combustible materials”
- Combustible solids and oxidizable metals should be kept away from molten-salt tanks
 - Use stainless steels or nickel-alloy materials
- Firefighting
 - Carbon dioxide and approved dry powder-type extinguishers should be used – no water of volatile liquids
 - Adequate supply of dry sand should be available for slagging and diking to confine the spread



Summary

- Concentrating solar power provides utility-scale electricity *and* energy storage
- Commercial CSP plants in operation with over 9 GWh of thermal energy storage
 - No safety incidents of molten nitrate salt storage since 2008
 - No safety incidents of solid media thermal storage

Questions?

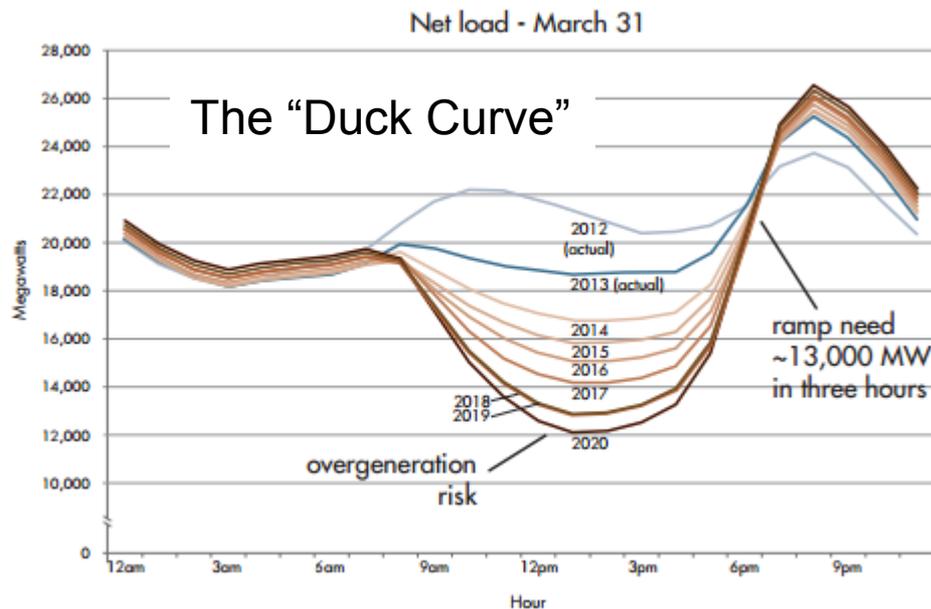


Cliff Ho, (505) 844-2384, ckho@sandia.gov

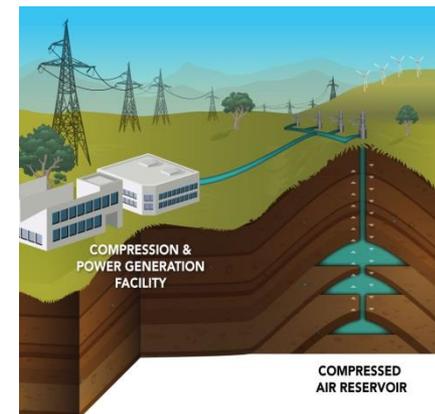
Backup Slides

Problem Statement

- Current renewable energy sources are intermittent
 - Causes curtailment or negative pricing during mid-day
 - Cannot meet peak demand, even at high penetration
- Available energy storage options for solar PV & wind
 - Large-scale battery storage is expensive
 - \$0.20/kWh_e - \$1.00/kWh_e
 - Compressed air and pumped hydro – geography and/or resource limited

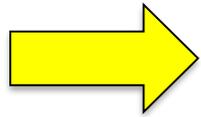


Source: California Independent System Operator



Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage



Concentrating solar power (CSP) with thermal energy storage

Comparison of Energy Storage Options

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost ¹ (\$/MWh _e)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency ²	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life ³	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/ environmental impacts	N/A	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	N/A	N/A
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

Thermal Energy Storage Goals

- Capable of achieving high temperatures (> 700 C)
- High energy and exergetic efficiency ($>95\%$)
- Large energy density (MJ/m^3)
- Low cost ($< \$15/\text{kWh}_t$; $< \$0.06/\text{kWh}_e$ for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid ($h > 100 \text{ W}/\text{m}^2\text{-K}$)

TABLE 1 | The Physical Properties of Selected Thermal Energy Storage Media. Sensible Energy Storage Media, Both Liquid and Solid, Are Assumed to Have a Storage Temperature Differential of 350°C with Respect to the Calculation of Volumetric and Gravimetric Storage Density

Storage Medium	Specific Heat (kJ/kg-K)	Latent or Reaction Heat (kJ/kg)	Density (kg/m ³)	Temperature Range (°C)		Gravimetric Storage Density (kJ/kg)	Volumetry Storage Density (MJ/m ³)	References
				Cold	Hot			
Sensible Energy Storage—Solids								
Concrete	0.9	—	2200	200	400	315	693	23
Sintered bauxite particles	1.1	—	2000	400	1000	385	770	24
NaCl	0.9	—	2160	200	500	315	680	23
Cast iron	0.6	—	7200	200	400	210	1512	25
Cast steel	0.6	—	7800	200	700	210	1638	23
Silica fire bricks	1	—	1820	200	700	350	637	23
Magnesia fire bricks	1.2	—	3000	200	1200	420	1260	25
Graphite	1.9	—	1700	500	850	665	1131	26
Aluminum oxide	1.3	—	4000	200	700	455	1820	27
Slag	0.84	—	2700	200	700	294	794	28
Sensible Energy Storage—Liquids								
Nitrate salts (ex. KNO ₃ -0.46NaNO ₃)	1.6	—	1815	300	600	560	1016	17
Therminol VP-1 [®]	2.5	—	750	300	400	875	656	29
Silicone oil	2.1	—	900	300	400	735	662	23
Carbonate salts	1.8	—	2100	450	850	630	1323	23
Caloria HT-43 [®]	2.8	—	690	150	316	980	676	25
Sodium liquid metal	1.3	—	960	316	700	455	437	25
Na-0.79K metal eutectic	1.1	—	900	300	700	385	347	30
Hydroxide salts (ex. NaOH)	2.1	—	1700	350	1100	735	1250	27
Latent Energy Storage								
Aluminum	1.2	397	2380	—	660	397	945	28
Aluminum alloys (ex. Al-0.13Si)	1.5	515	2250	—	579	515	1159	31, 32
Copper alloys (ex. Cu-0.29Si)	—	196	7090	—	803	196	1390	32
Carbonate salts (ex. Li ₂ CO ₃)	—	607	2200	—	726	607	1335	32
Nitrate salts (ex. KNO ₃ -0.46NaNO ₃)	1.5	100	1950	—	222	100	195	28
Bromide salts (ex. KBr)	0.53	215	2400	—	730	215	516	33
Chloride salts (ex. NaCl)	1.1	481	2170	—	801	481	1044	33
Fluoride salts (ex. LiF)	2.4	1044	2200	—	842	1044	2297	33
Lithium hydride	8.04	2582	790	—	683	2582	2040	31
Hydroxide salts (ex. NaOH)	1.47	160	2070	—	320	160	331	31
Thermochemical Energy Storage								
SO ₂ (g) ↔ SO ₂ (s) + 1/2O ₂ (g)	—	1225	—	—	650	1225	—	28, 30, 34
CaCO ₃ (s) ↔ CO ₂ (g) + CaO(s)	—	1757	—	—	527	1757	—	28, 34
CH ₄ (g) + CO ₂ (g) ↔ 2CO(g) + 2H ₂ (g)	—	4100	—	—	538	4100	—	35
CH ₄ (g) + H ₂ O(g) ↔ 3H ₂ (g) + CO(g)	—	6064	—	—	538	6064	—	35
Ca(OH) ₂ (s) ↔ CaO(s) + H ₂ O(g)	—	1351	—	—	521	1351	—	28, 30, 34
NH ₃ (g) ↔ 1/2N ₂ (g) + 3/2H ₂ (g)	—	3900	—	—	195	3900	—	36

Siegel (2012)