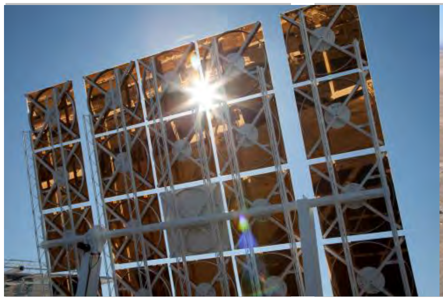
Concentrating Solar Power and Thermal Energy Storage

Exceptional service in the national interest



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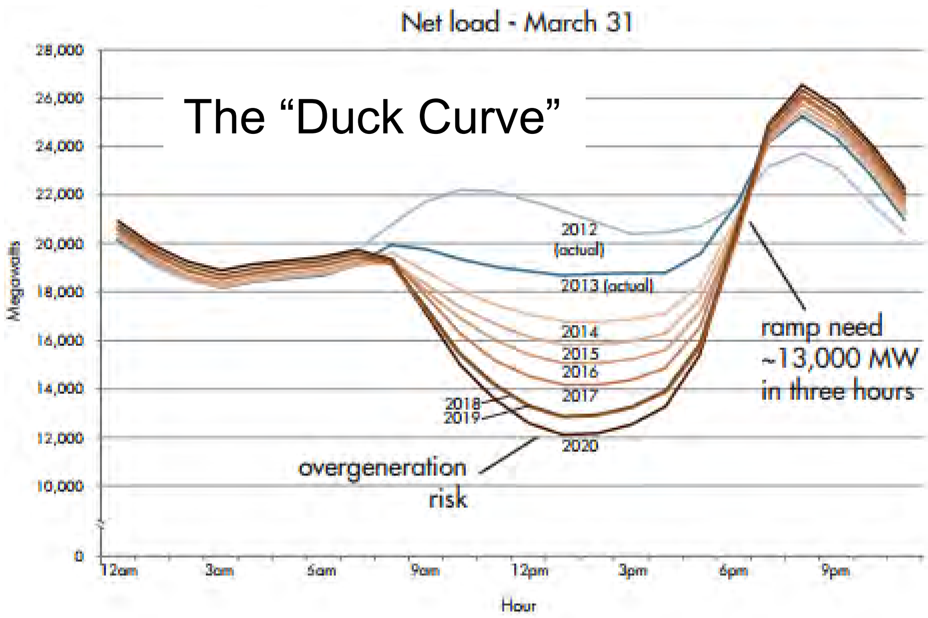
Outline

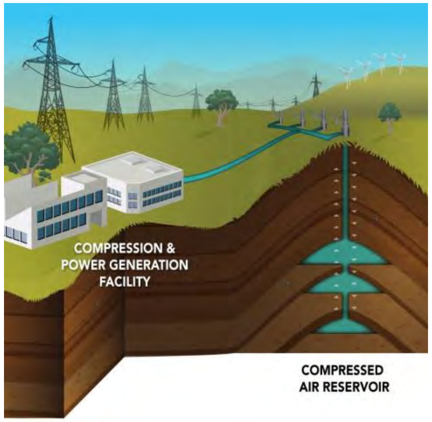
- Problem Statement
- What is Concentrating Solar Power (CSP)?
- Thermal Storage Options and Challenges
- Summary

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

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What is Concentrating Solar Power (CSP)?

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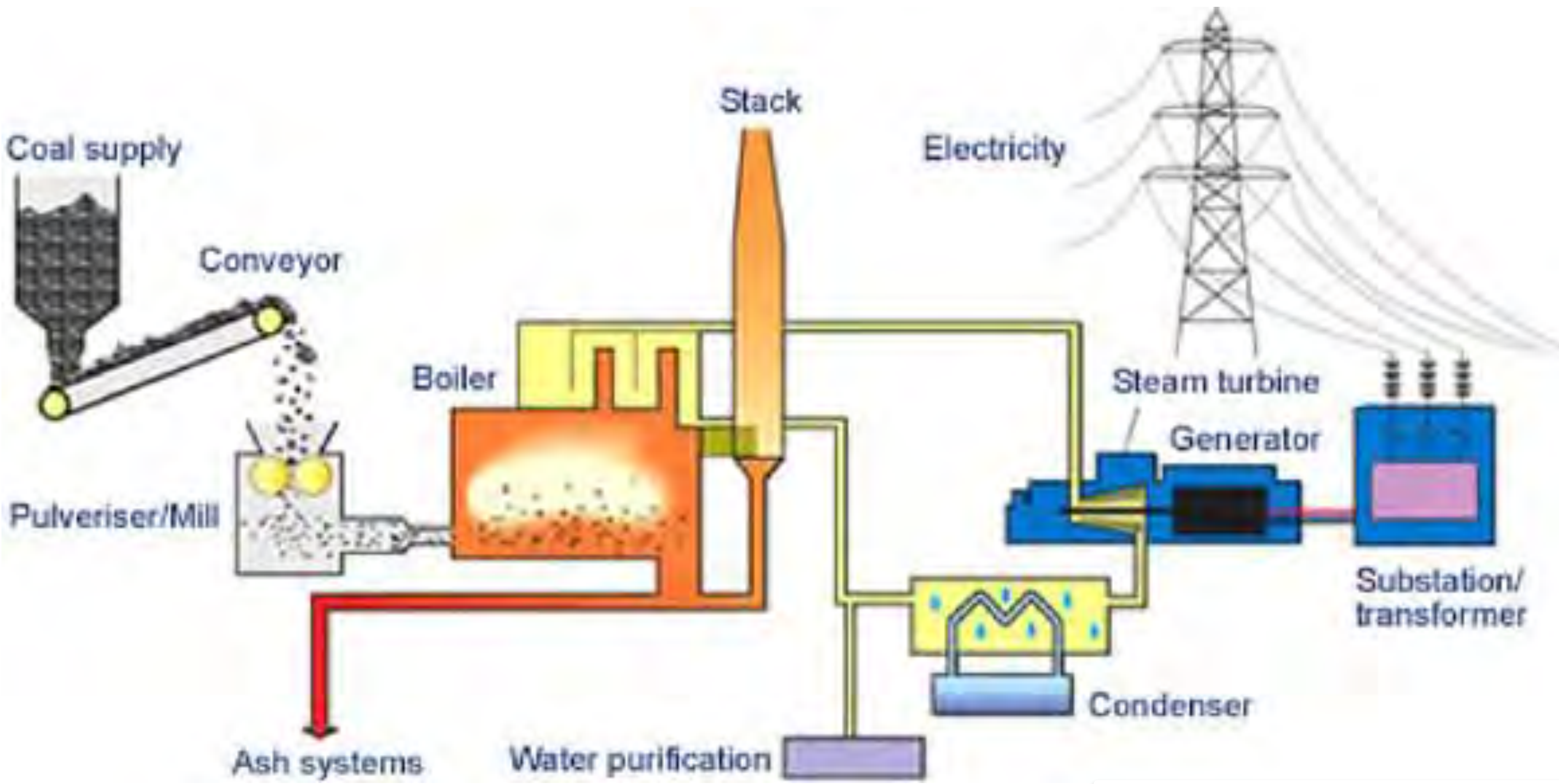
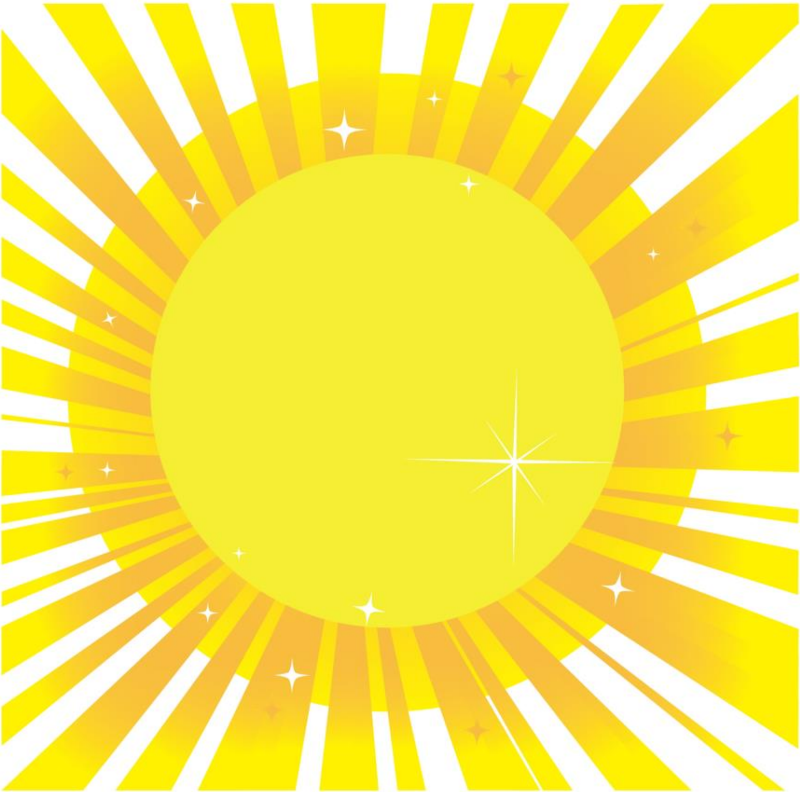
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

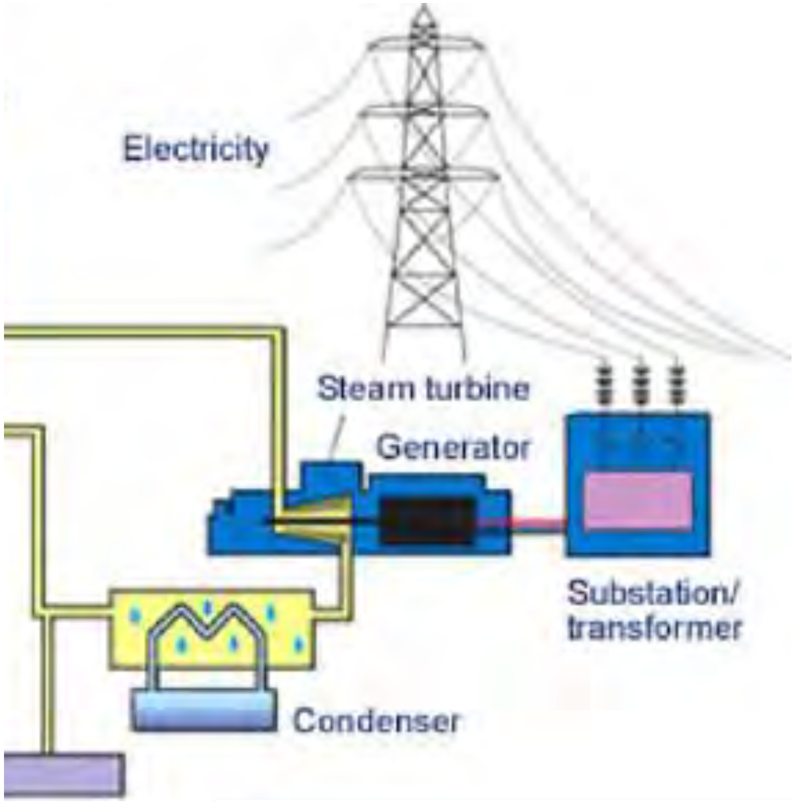


Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

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

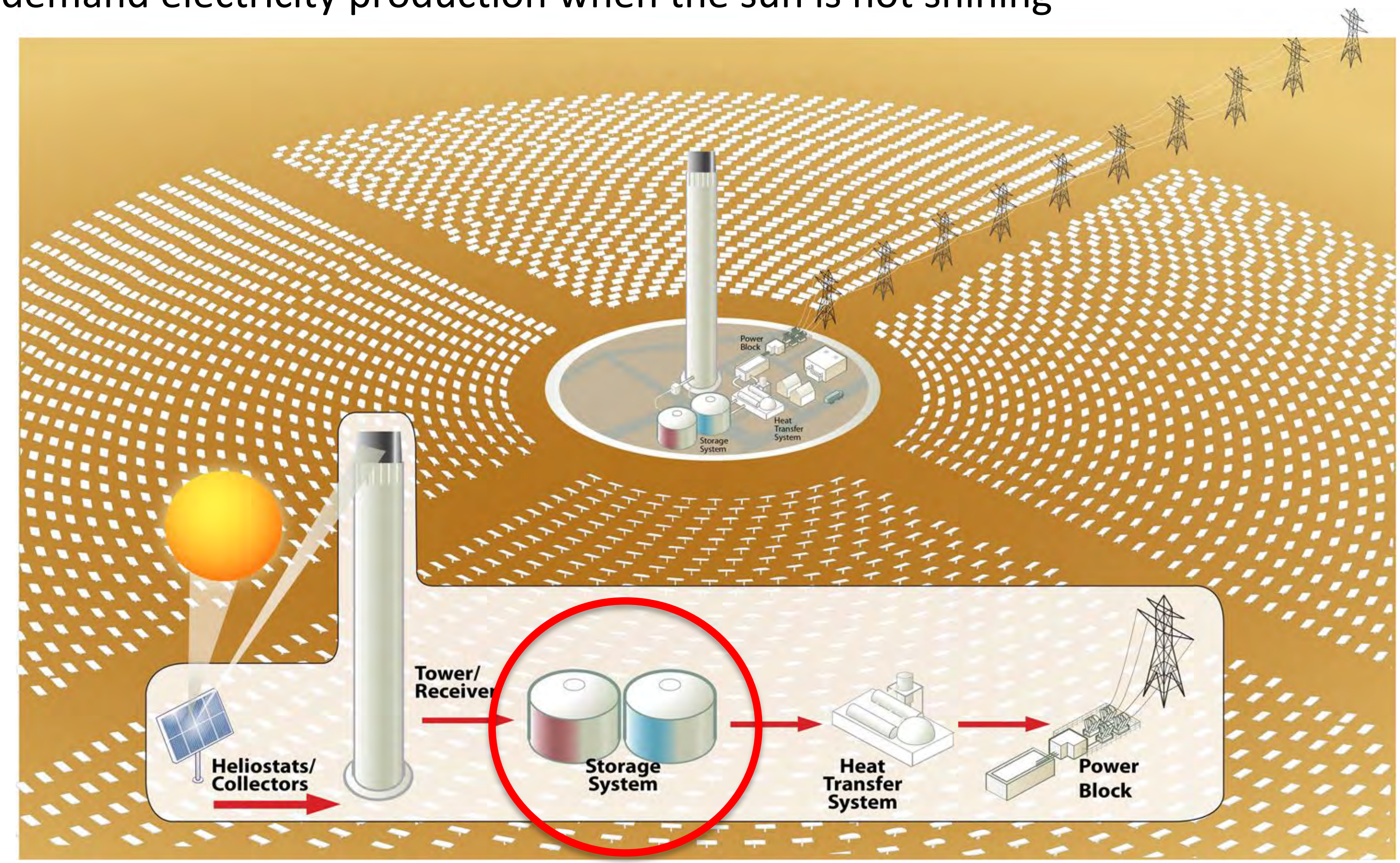




Concentrating Solar Power

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



Commercial CSP Plants

Ivanpah Solar Power Tower

California (near Las Vegas, NV)

http://news.nationalgeographic.com

392 MWe direct-steam power tower plants in Ivanpah, CA. 170,000 heliostats. Opened February 2014

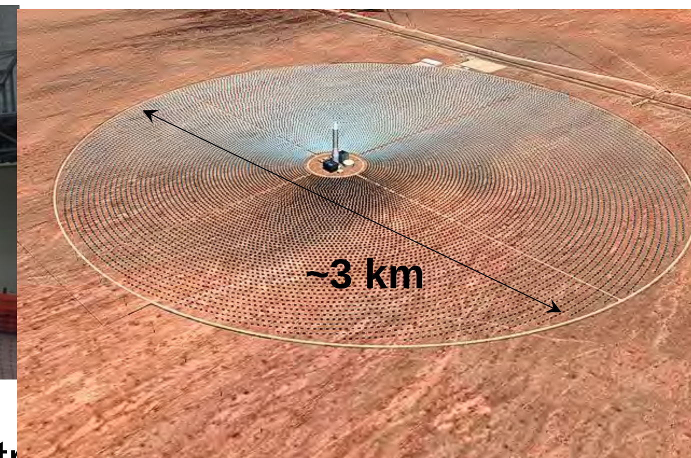
Gemasolar

(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). Commissioned in May 2011.

Crescent Dunes

Tonopah, Nevada



110 MWe molten-salt power tower under constr
near Tonopah, NV. Construction from 2011 – 2015.

Solana Generating Station

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

6 hours of molten-salt storage

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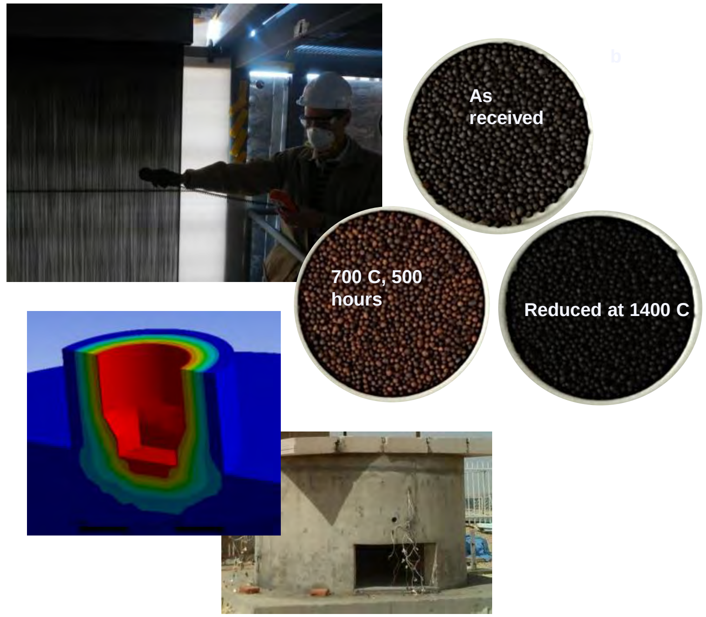
Types of Thermal Energy Storage

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

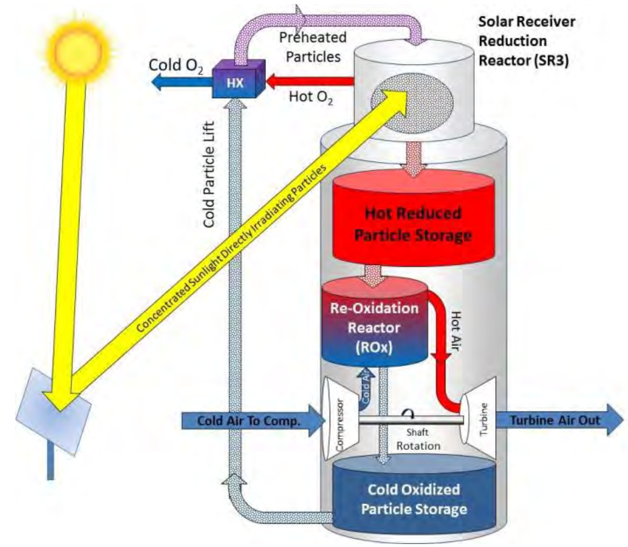
Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Sandia Research in Thermal Energy Storage

Corrosion studies in molten salt up to 700 C in “salt pots”

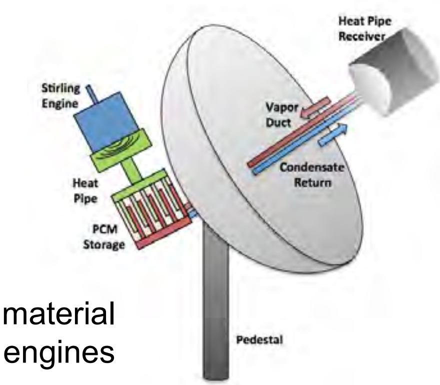


Ceramic particle storage and heating with falling particle receiver



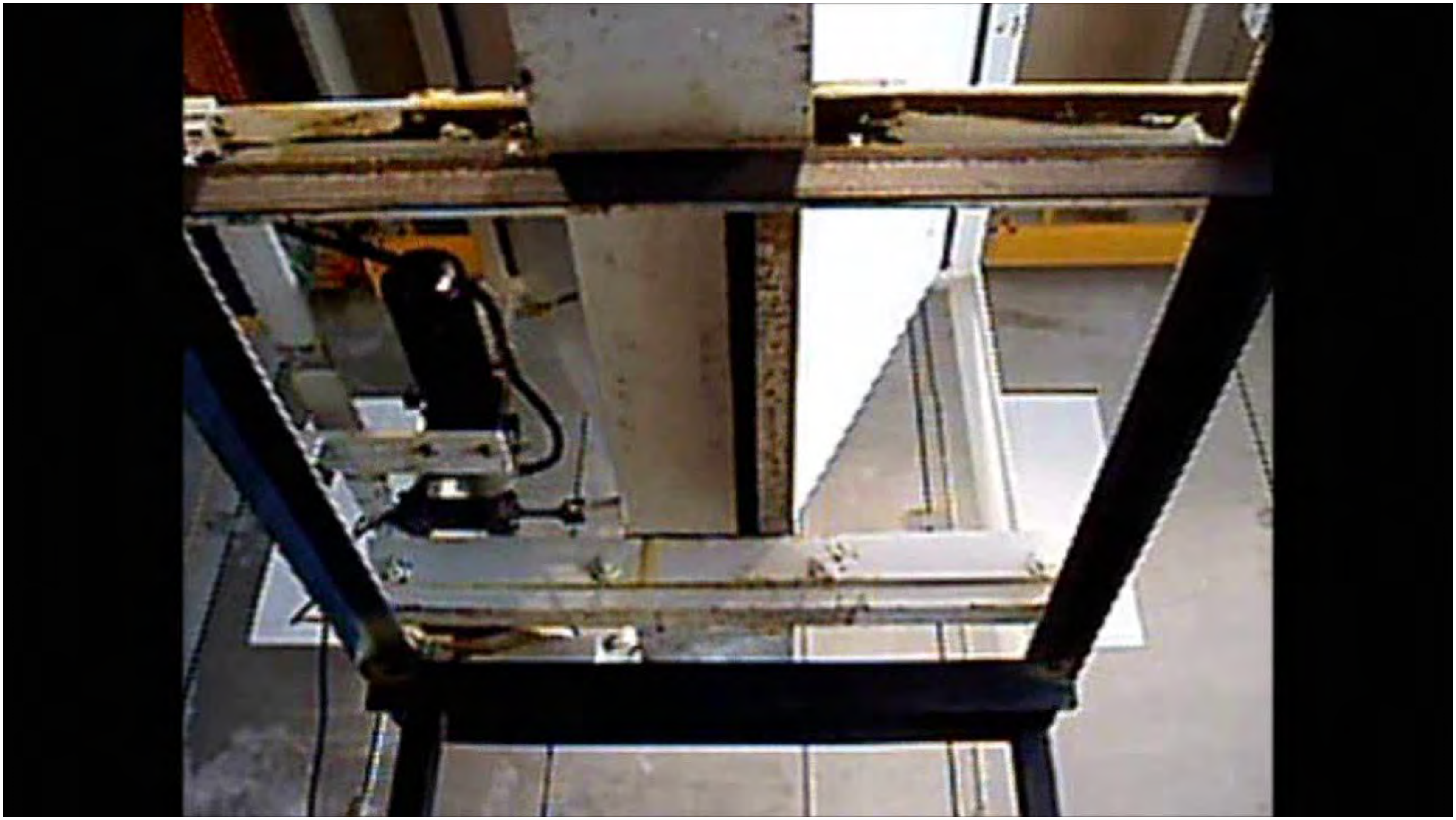
Thermochemical particle storage with reduction/oxidation of perovskites

Component testing with molten-salt test loop



Latent phase-change material storage in dish engines

Particle Receiver Designs – Free Falling



On-Sun Tower Testing

Over 600 suns peak flux on receiver
(July 20, 2015)

On-Sun Tower Testing

Particle Flow Through Mesh Structures
(June 25, 2015)

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Summary

- Renewables require energy storage for increased penetration
- Concentrating solar power provides utility-scale electricity AND energy storage
- Thermal energy storage options
  - Sensible heat storage (molten salt, particles)
  - Latent heat storage
  - Thermochemical storage
- Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage

Questions?

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Backup Slides

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 (<$15/$kWh_t$; <$0.06/kWh_e for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid ($h > 100\ W/m^2$-K)

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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/m³)	Temperature Range (°C)		Gravimetric Storage Density (kJ/kg)	Volumetric Storage Density (MJ/m³)	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_3-0.46$NaNO_3$)	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_2CO_3)	–	607	2200	–	726	607	1335	32
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	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
Flouride 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								
$SO_3(g) \leftrightarrow SO_2(s) + 1/2O_2(g)$	–	1225	–	–	650	1225	–	28, 30, 34
$CaCO_3(s) \leftrightarrow CO_2(g) + CaO(s)$	–	1757	–	–	527	1757	–	28, 34
$CH_4(g) + CO_2(g) \leftrightarrow 2CO(g) + 2H_2(g)$	–	4100	–	–	538	4100	–	35
$CH_4(g) + H_2O(g) \leftrightarrow 3H_2(g) + CO(g)$	–	6064	–	–	538	6064	–	35
$Ca(OH)_2(s) \leftrightarrow CaO(s) + H_2O(g)$	–	1351	–	–	521	1351	–	28, 30, 34
$NH_3(g) \leftrightarrow 1/2N_2(g) + 3/2H_2(g)$	–	3900	–	–	195	3900	–	36

Siegel (2012)