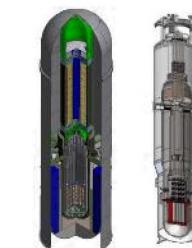


Zero-Carbon Emission Power Generation Technologies



SAND2019-14235PE



PRESENTED BY

Clifford K. Ho and Danielle Redhouse



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Introduction



**Sandia is one of 17 U.S.
National Laboratories**

- National Nuclear Security Administration labs
- Science labs
- Nuclear energy lab
- Environmental management lab
- Fossil energy lab
- Energy efficiency and renewable energy lab

Sandia's National Security Mission

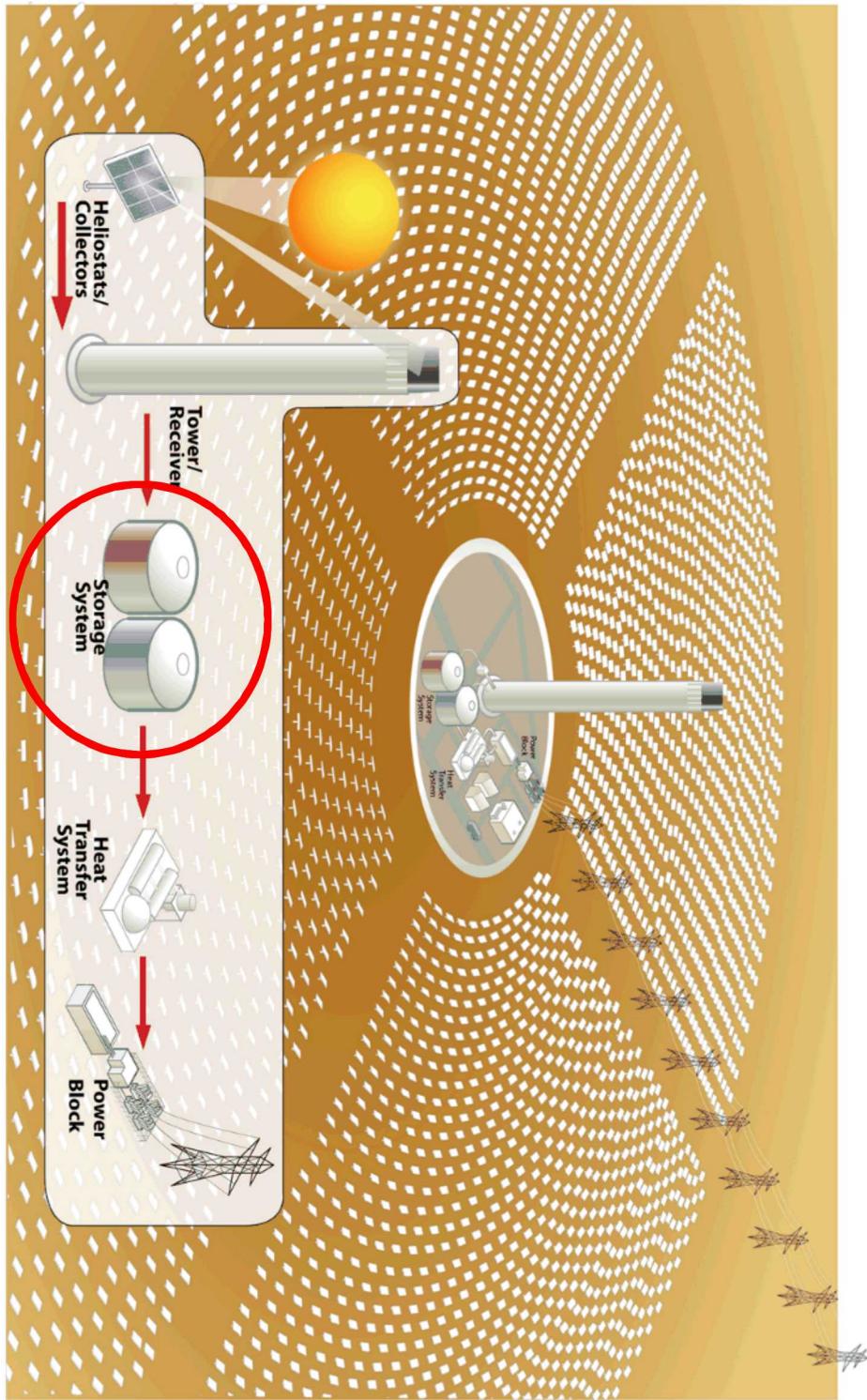
- Nuclear Deterrence
- Nuclear Nonproliferation
- National Security Programs
- Energy & Homeland Security
- Advanced Science & Technology

Energy Research at Sandia

- Renewable Energy
 - Solar photovoltaics
 - Concentrating solar thermal power
 - Wind energy
 - Marine and hydrokinetic energy
 - Geothermal energy
- Energy Storage
 - Thermal, thermochemical
 - Batteries
 - Hydrogen
- Nuclear Energy
 - Small modular reactors

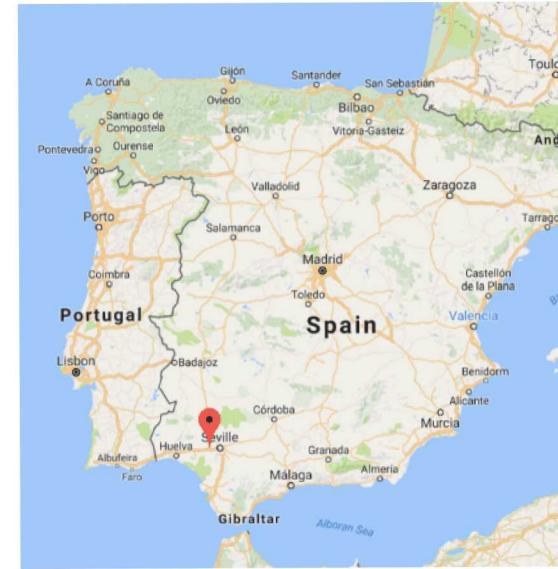
CSP and Thermal Energy Storage

- 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**



PS10 and PS20 (Seville, Spain)

- First commercial power tower plants in the world (2007, 2009)
- 11 MW and 20 MW
- Saturated steam
 - 250 C, 45 bar steam, wet cooling



Ivanpah Solar Power Tower

California (near Las Vegas, NV)



<http://news.nationalgeographic.com>



Three towers, 392 MWe, superheated-steam at 540 C, 160 bar, air-cooled (2014)



Ryan Goerl, NRG

Gemasolar

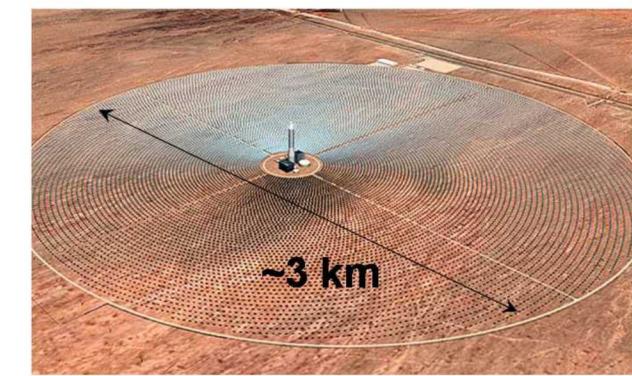
(near Seville, Spain)



- 1st commercial power tower (19 MW) in the world with “24/7 dispatchable energy production” (15 hours of thermal storage using molten salt), wet cooling. Commissioned in May 2011.

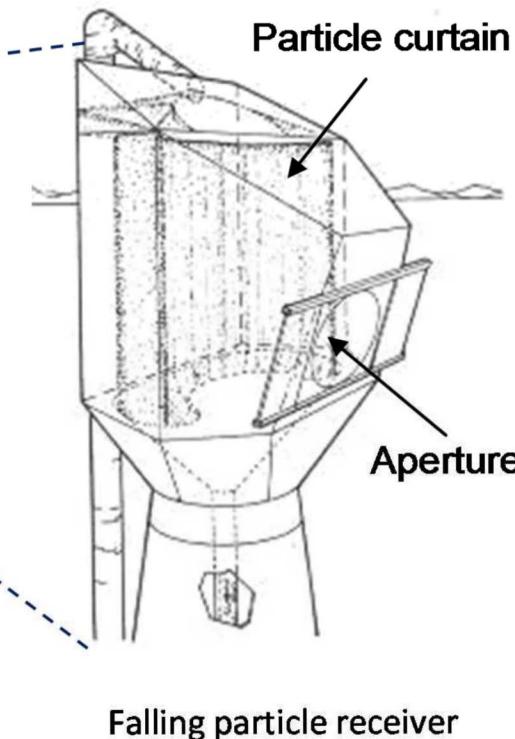
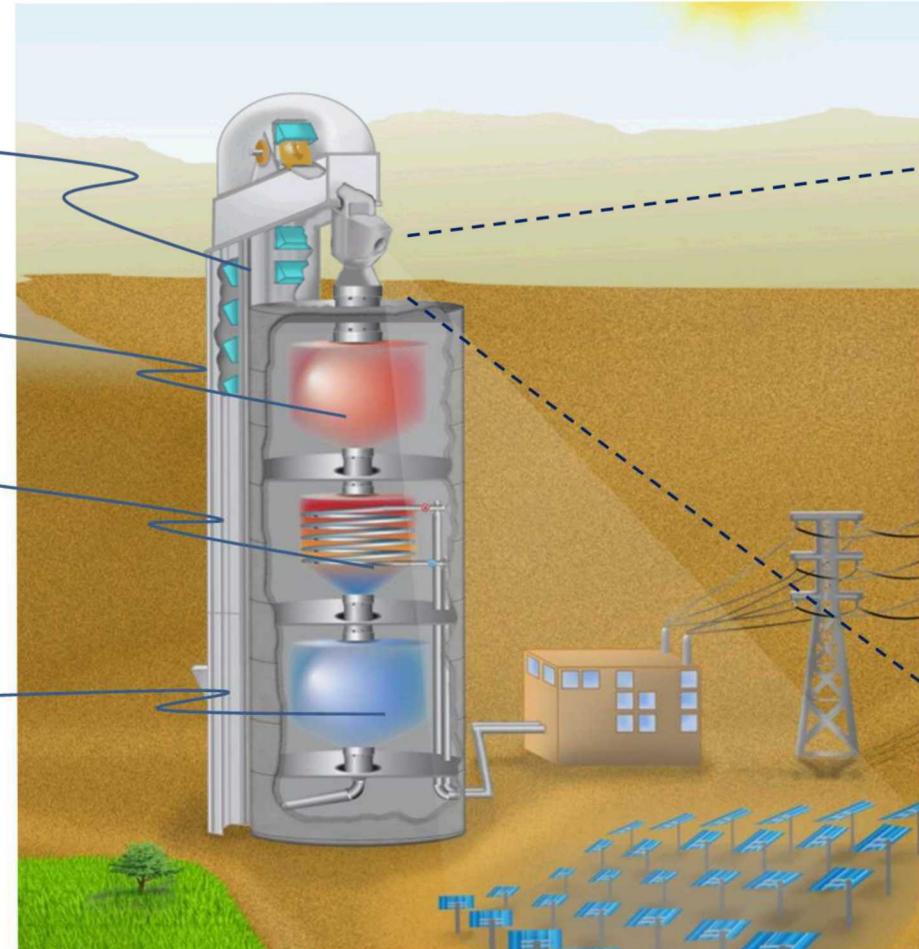
Crescent Dunes

Tonopah, Nevada



110 MWe, 570 C molten-salt, 10 hours of storage, hybrid air-cooled condenser (2015)

High Temperature Falling Particle Receiver



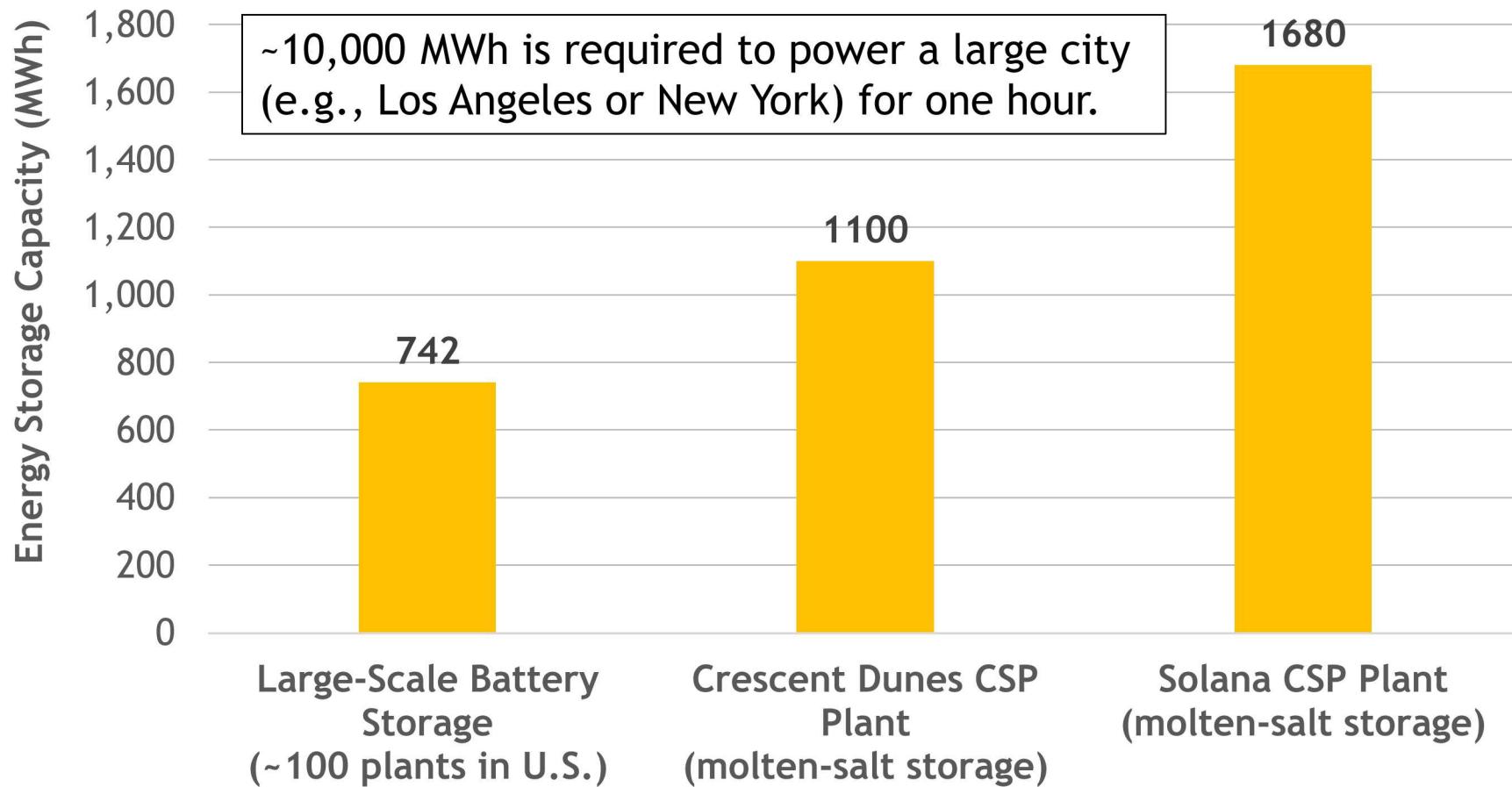
National Solar Thermal Test Facility
Sandia National Laboratories

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Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.

Battery data from U.S. Energy Information Administration (June 5, 2018);
CSP data from solarpaces.nrel.gov/projects



Solana Generating Station



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



futureenergyweb.es



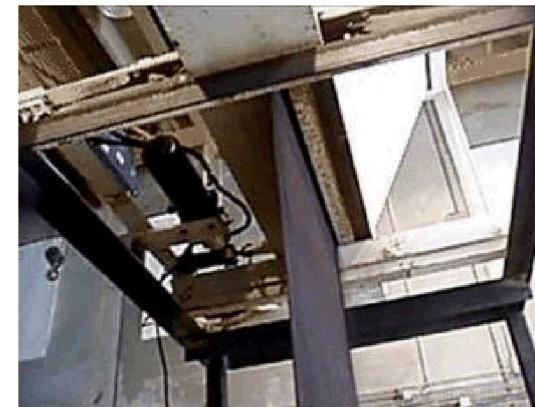
6 hours of molten-salt storage
heated from ~300 - 400 C
(1.7 GWh)

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

Energy Storage R&D at Sandia

Hydrogen Storage

Sandia's Hydrogen and Fuel Cells program is developing technologies to accelerate large-scale deployment of hydrogen storage.



Thermal Storage

Sandia's Concentrating Solar Power (CSP) program is developing molten salt thermal storage systems for grid-scale energy storage.



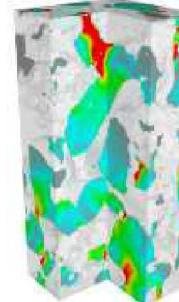
Battery Materials

Sandia has a large portfolio of R&D projects related to advanced materials to support the development of lower cost energy storage technologies including new battery chemistries, electrolyte materials, and membranes.



Systems Modeling

Sandia is performing research in a number of areas on the reliability and safety of energy storage systems including simulation, modeling, and analysis, from cell components to fully integrated systems.



Systems Analysis

Sandia has extensive infrastructure to evaluate megawatt-hour class energy storage systems in a grid-tied environment to enable industry acceptance of new energy storage technologies.



Cell & Module Level Safety

Sandia has exceptional capabilities to evaluate fundamental safety mechanisms from cell to module level for applications ranging from electric vehicles to military systems.



Power Conversion Systems

Leveraging exceptional strengths in power electronics, Sandia has unique capabilities to characterize the reliability of power electronics and power conversion systems.



Grid Analytics

Analytical and multi-physics models to understand risk and safety of complex systems, optimization, and efficient utilization of energy storage systems in the field.



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Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

Sandia Hydrogen R&D



Sandia provides deep, quantitative understanding and a scientific basis for...

Materials – for hydrogen production, storage and utilization

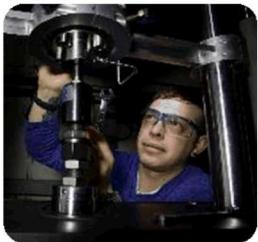
Safety – risk analysis and the creation of risk-informed standards

Hydrogen Production from Renewables



Advanced water-splitting materials and technologies for large-scale H₂ production

Hydrogen-Materials Compatibility

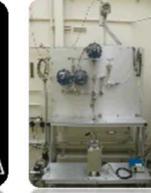
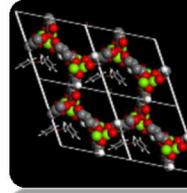
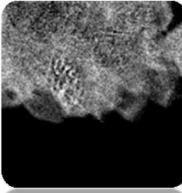


Low-cost, hydrogen-compatible materials and the science basis for their qualification

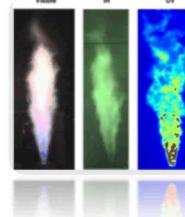


Hydrogen Storage Materials and Solutions

Discovering the behavior and performance of solid storage materials



Hydrogen Fueling Infrastructure



H₂ release behavior and risk assessment to define the safety envelope for storage & delivery

Technologies for Non-Vehicle Applications

Marine and rail applications



Fuel Cells

Membrane systems for enhanced electrochemical performance



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 |

¹Ho, C.K., A Review of High-Temperature Particle Receivers for Concentrating Solar Power, *Applied Thermal Energy*, 2016; Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011, Power Tower Technology Roadmap and Cost Reduction Plan, SAND2011-2419, Sandia National Laboratories, Albuquerque, NM; Akhil et al., 2015, DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, SAND2015-1002, Sandia National Laboratories, Albuquerque, NM. For solid particles and molten salt, we assume a 30 - 50% thermal-to-electric conversion efficiency and 10,000 lifetime cycles for the thermal-to-electric storage and conversion systems; the cost includes the storage media (bulk ceramic particles and sodium/potassium nitrate salts ~\$1/kg with $\Delta T = 400$ °C and 9 hours of storage), tanks, pumps/piping/valves, other parts and contingency, and the power block at \$1000/kW_e with 19 operating hours per daily cycle (including 9 hrs of storage) and 90% availability. For batteries, cost is based on sodium-sulfur, vanadium-redox, zinc-bromine, lead-acid, and lithium-ion batteries capable of providing large-scale electricity.

²Roundtrip efficiency defined as ratio of energy in to energy retrieved from storage; Djajadiwinata, E. et al., 2014, Modeling of Transient Energy Loss from a Cylindrical-Shaped Solid Particle Thermal Energy Storage Tank for Central Receiver Applications, Proceedings of the Asme 8th International Conference on Energy Sustainability, 2014, Vol 1.; Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.; <http://energystorage.org/energy-storage/energy-storage-technologies/>

³Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.

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Danielle will add slides