NREL
Transforming ENERGY

Solar Thermal Energy Storage: Salt, Sand, Brine and Electrons

Craig Turchi

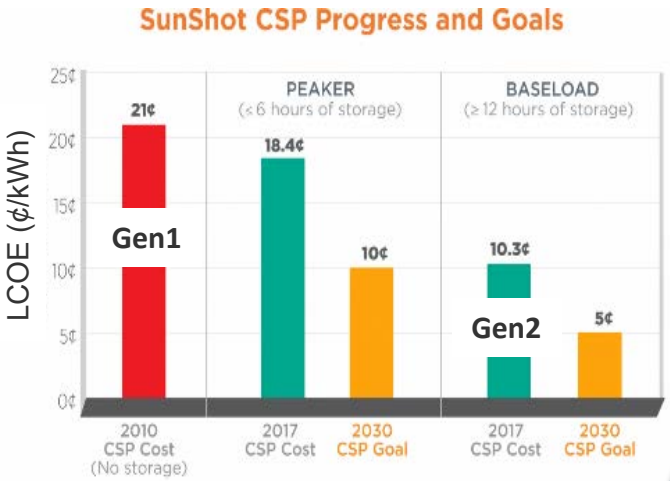
Group Manager, Thermal Energy Science & Technologies
Program Leader, NREL Concentrating Solar Thermal

Thermal-Mechanical-Chemical Energy Storage Workshop
Charlotte, NC, July 31-August 1, 2024

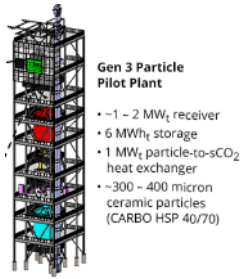
Outline

1. Solar Thermal TES State-of-the-Art: Molten Salt
2. Solar Thermal TES next Generation: Particles
3. ETES: Electrically heated TES
4. CSP+TES Potential: California SB100 Analysis
5. GeoTES
6. Summary

Evolution of CSP Technology



Gen3 CSP Current Research



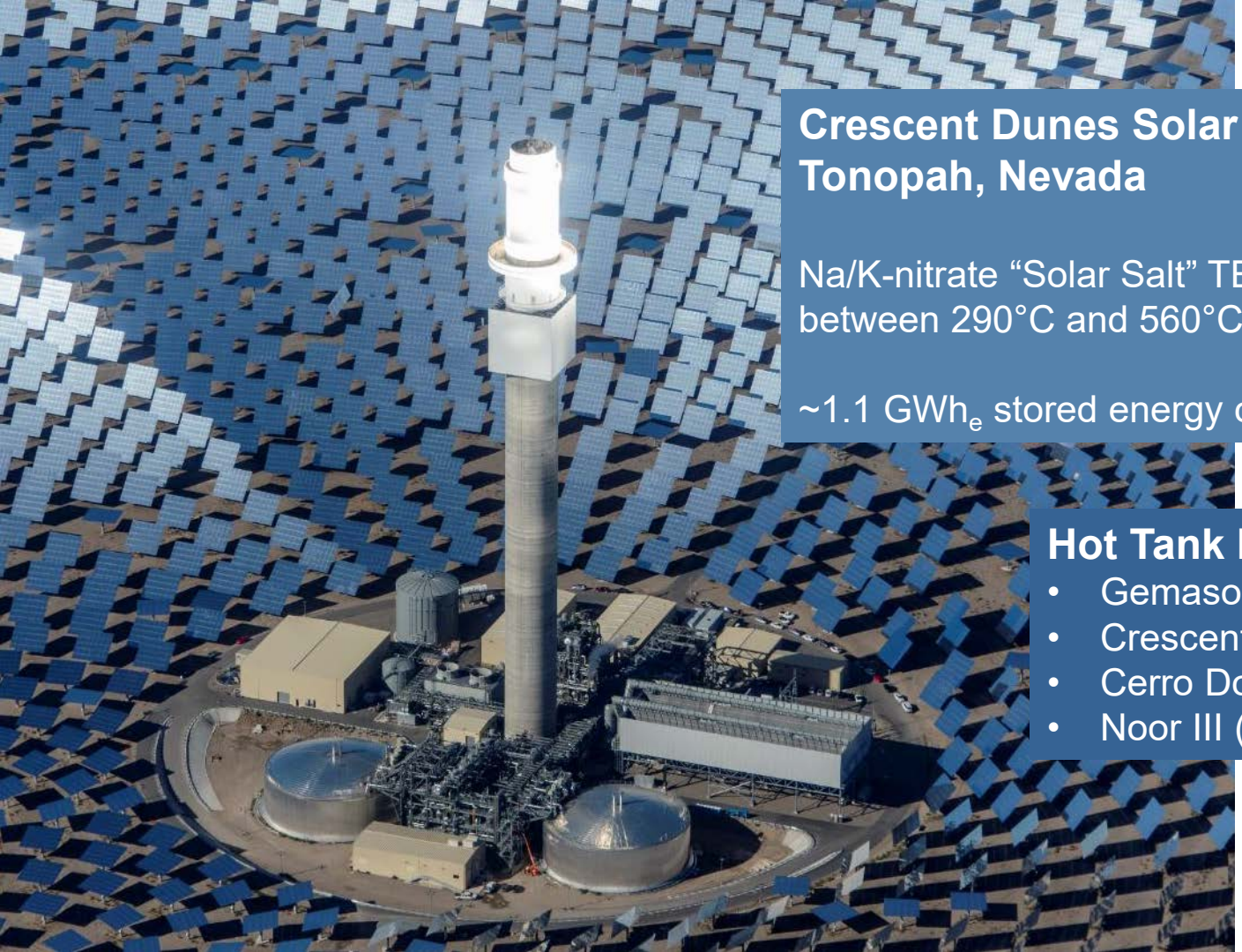
- Power Tower
- Hot-Particle Storage @ 750°C
- 12+ hours storage
- Supercritical-CO_2 power cycle with 50% efficiency

Generation 2 2010s

- Power Tower
- Molten Salt Storage @ 560°C
- 10 hours storage
- Steam power cycle with 42% efficiency

Generation 1 1980s-2000s

- Parabolic Trough
- Thermal Oil @ 390°C
- No storage
- Steam power cycle with 38% efficiency



Crescent Dunes Solar Energy Plant
Tonopah, Nevada

Na/K-nitrate “Solar Salt” TES operating between 290°C and 560°C

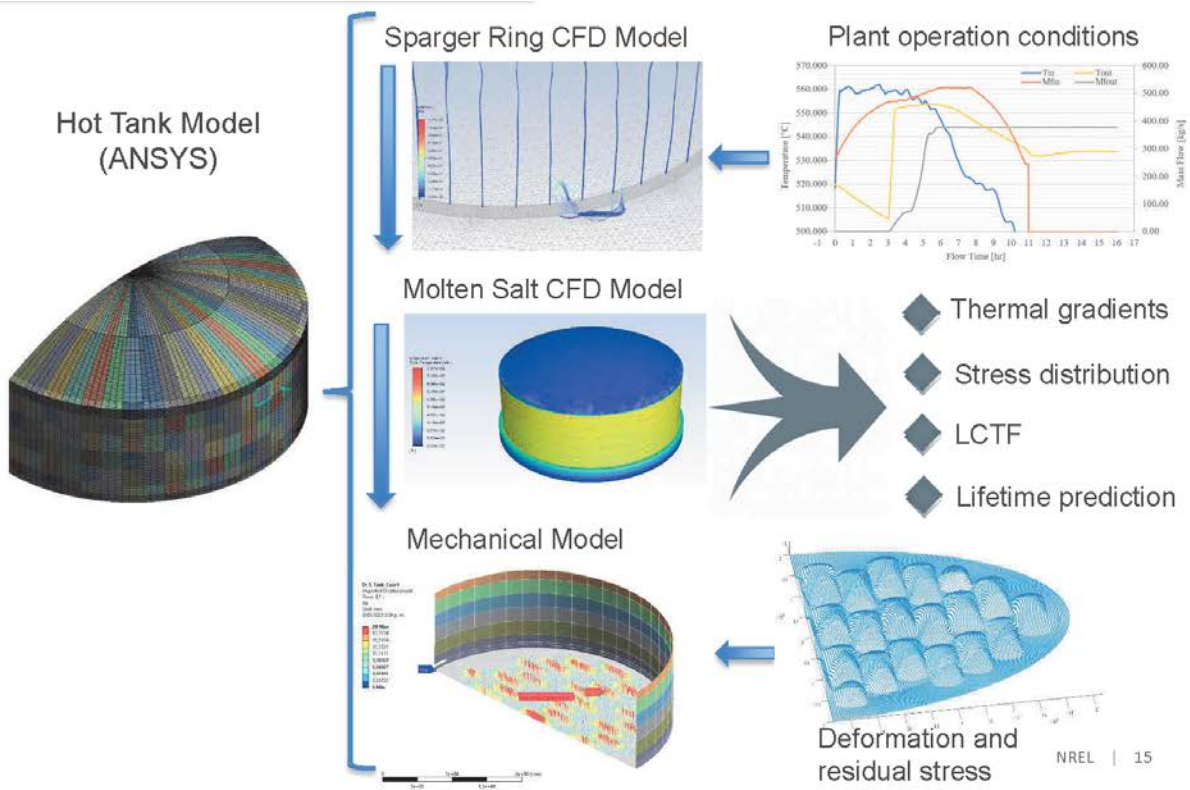
~1.1 GWh_e stored energy capacity

Hot Tank leaks at:

- Gemasolar (Spain)
- Crescent Dunes (USA)
- Cerro Dominador (Chile)
- Noor III (Morocco)

Molten Salt Hot Tank Modeling

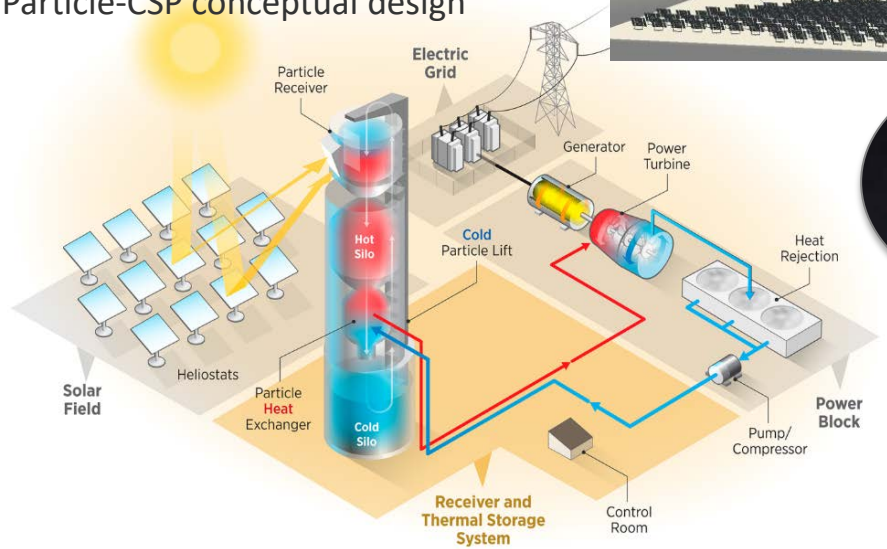
The hot tank model has been validated. It incorporates computational fluid dynamics (CFD) models for the sparger ring and molten salt and a mechanical model for the tank shell and floor.



Osorio et al., *Failure Analysis for Molten Salt Thermal Energy Storage Tanks for In-Service CSP Plants*
https://doi.org/10.2172/2331241

Gen3 CSP Particle Pilot Plant (G3P3)

Particle-CSP conceptual design



G3P3 tower at National Solar Thermal Test Facility, Sandia National Laboratories.

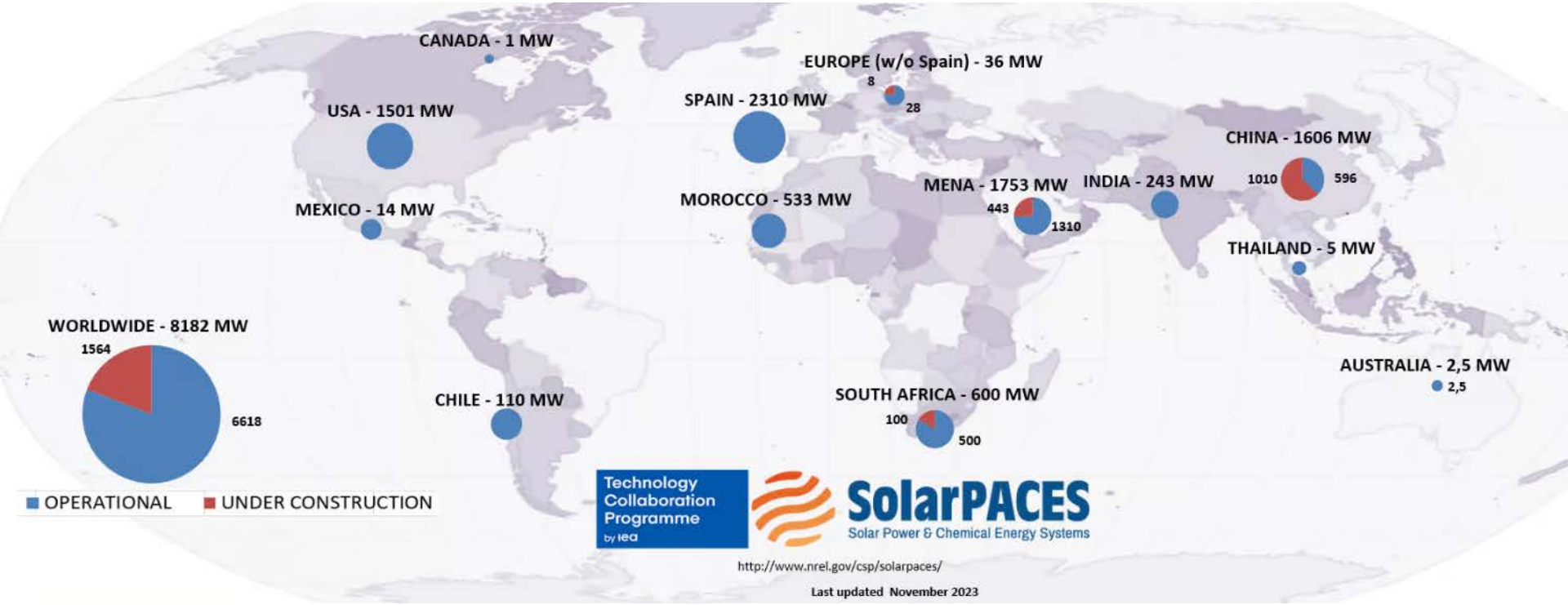
https://energy.sandia.gov/programs/renewable-energy/csp/current-research-projects/gen-3-particle-pilot-plant-g3p3/

Solar Thermal TES: Salt vs. Particles

Property or Challenge	**Solar Salt** 60:40 $NaNO_3/KNO_3$	**Carboceramic Particles** Carbo HSP 40/70
Upper temperature limit	~560°C	>750°C
Lower temperature limit	Liquidus near 230°C	none
Cost	~$1400/$m^3$	~$3500/$m^3$
Technology Readiness Level of TES system	9 - Commercial	6 – Demonstration
Primary challenges	Hot tank and steam generation system durability under thermal cycling	Particle transport and heat transfer efficiency Particle receiver design

Z. Ma, et al., *Thermal Energy Storage For Energy Decarbonization*, in Annual Review of Heat Transfer, Volume:25, Page(s):51-115

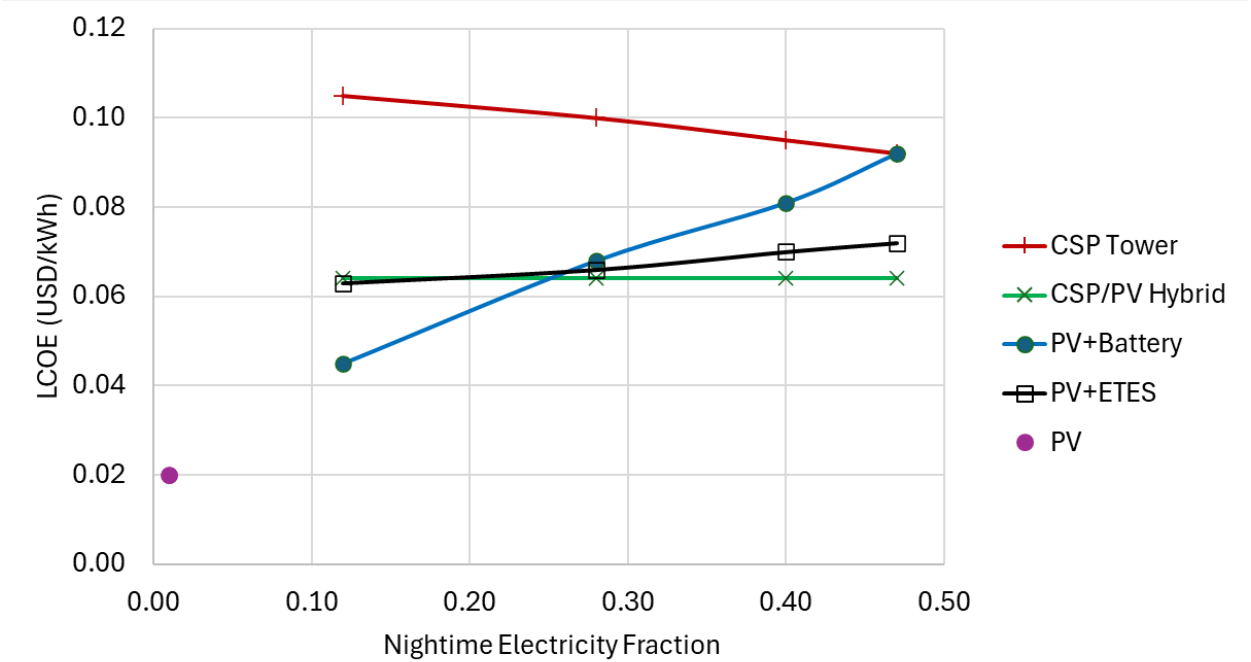
CSP Projects around the World



Global cumulative operational capacity ~ 6.6 GW_e

New CSP Plants are built as CSP+TES+PV Hybrids

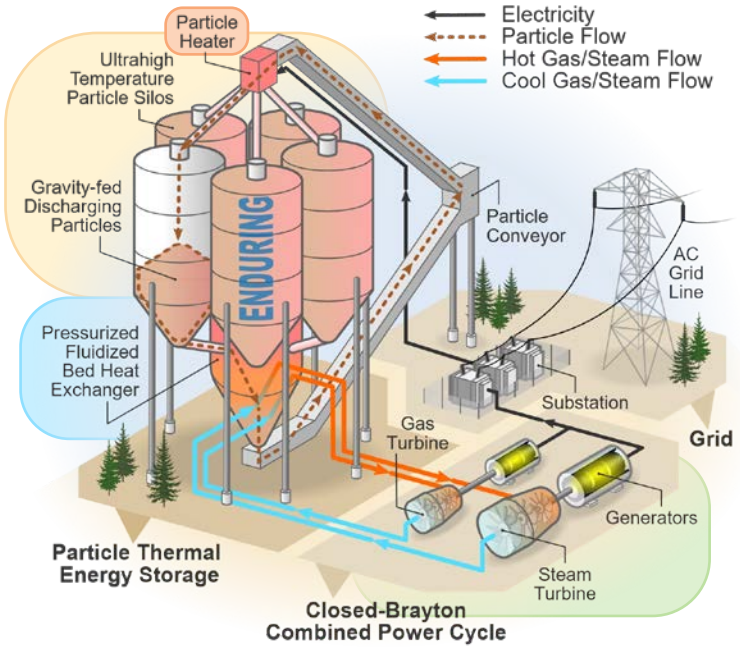
Lowest levelized cost of electricity (LCOE) for solar plant configurations in Riyadh, Saudi Arabia.



Notes:
- PV+ETES system has PV charging thermal energy storage (power-to-heat), which discharges thru a heat engine.
- Nighttime fractions correspond to 3, 6, 9, and 12 hours of storage.

Reproduced from Energies **2022**, 15, 7103. https://doi.org/10.3390/en15197103

Electrically Heated Thermal Energy Storage (ETES)



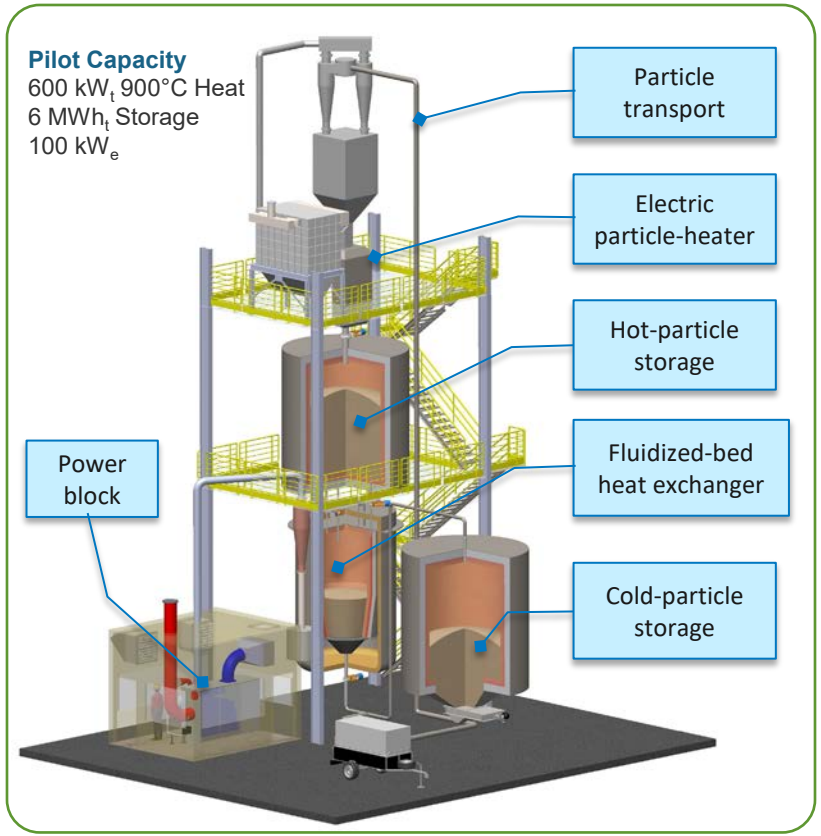
Developed under
Advanced Research Projects Agency – Energy (ARPA-E) U.S. Department of Energy

Significance & Impact:

- Low-cost sand used for thermal storage.
- Can integrate with commercial air-Brayton and/or steam power systems
- Provides power (or heat) for several days, enabling large-scale grid integration of variable renewables like wind and solar PV.
- The “ENDURING” system is designed to be deployed economically anywhere in the United States.

Ma, Zhiwen. 2023. Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle (ENDURING). Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-84728. https://www.nrel.gov/docs/fy23osti/84728.pdf

ETES Pilot System Demonstration at NREL

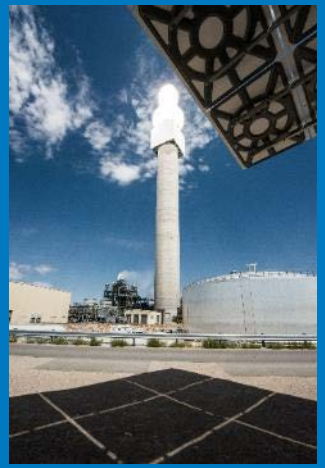


- Funded by DOE Office of Clean Energy Demonstrations
- Core of the project is 900°C thermal energy storage (TES) using sand.
- Technology leverages fossil-energy expertise throughout supply chain, including workforce.
- Construction to start in FY26
- After OCED-funded project completion, the TES asset will be utilized for industrial decarb R&D. The system will serve as a high-temperature testbed for industry-collaboration projects within NREL's Advanced Research on Integrated Energy Systems (ARIES) platform.

Ivanpah CSP Plant in California
NREL image 46269
Direct steam power tower → no storage!

CSP in the USA

Solana CSP Plant in Arizona, courtesy Abengoa Solar
Parabolic trough plant with 6-h storage → too expensive!



Last U.S. CSP plant was commissioned in 2015.

Crescent Dunes CSP Plant in Nevada
NREL image 46197
Molten-salt power tower with 10-h storage → reliability issues!

CSP Deployment Potential in the USA

California Senate Bill (SB100):
"The 100 Percent Clean Energy Act of 2018"

- California concluded SB100 is technically achievable through multiple pathways, e.g., "core" scenario by 2045 required:
  - ~100 GW of new solar power (utility scale and rooftop)
  - >20 GW of new wind generation (on-shore and off-shore)
  - >50 GW of energy storage
  - Construction of clean electricity generation and storage facilities sustained at record-setting rates
- California **did not include CSP** in its initial SB100 modeling assessment:

  Because of the higher costs relative to solar photovoltaic and wind energy, there is limited development potential, and solar thermal plants were ruled out of the modeling study.

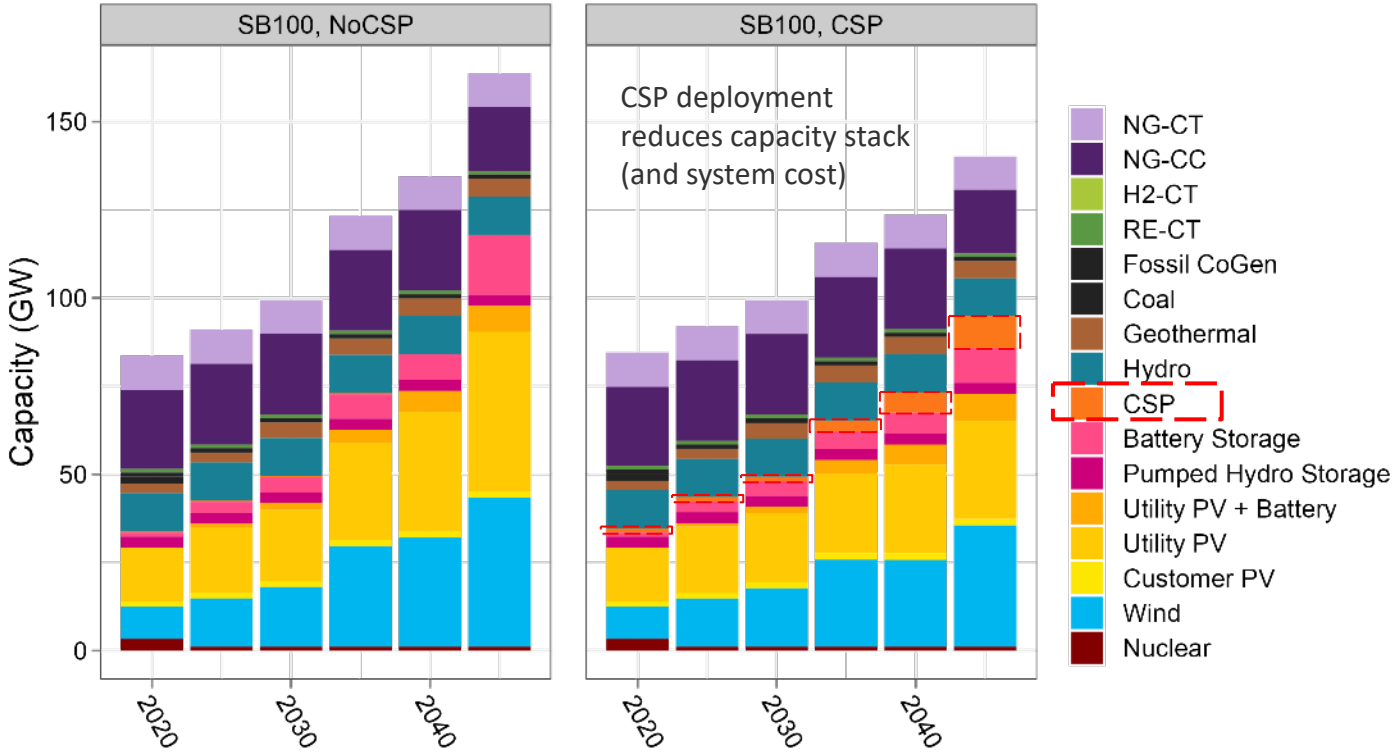
https://www.energy.ca.gov/publications/2021/2021-sb-100-joint-agency-report-achieving-100-percent-clean-electricity
https://efiling.energy.ca.gov/EFiling/GetFile.aspx?tn=237167&DocumentContentId=70349

NREL Replicated SB100 Analysis with Inclusion of CSP

- NREL's Regional Planning Model (RPM) capacity-expansion model used to replicate several SB100 scenarios
- Assumed mid-case 2022 Annual Technology Baseline (ATB) costs for all technologies.
  - Mid-case CSP is 560°C molten-salt Tower with an sCO_2 power cycle
- Evaluated specific zones for CSP development and explored what assumptions were necessary for CSP deployment to help meet SB100 goals

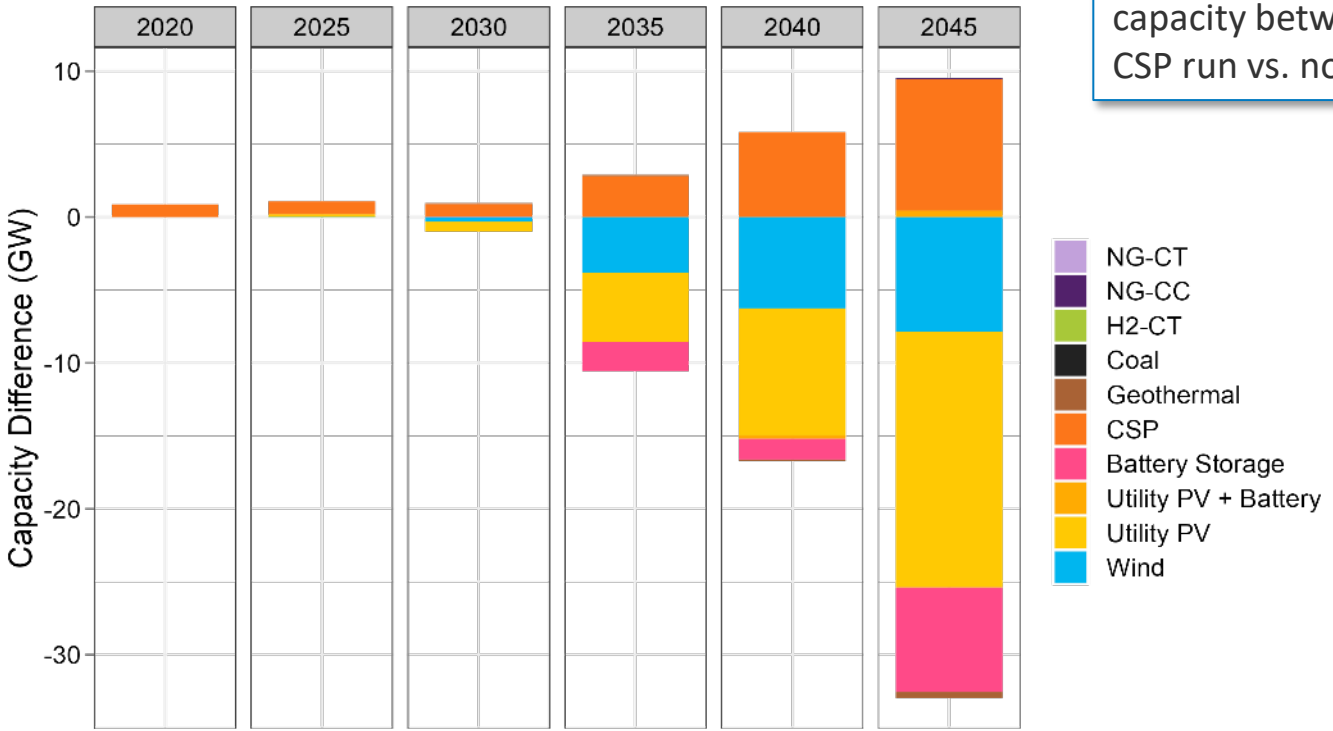
https://atb.nrel.gov/

SB100 Results: Installed Capacity



SB100 Results: Installed Capacity Difference

Difference in installed capacity between CSP run vs. noCSP run

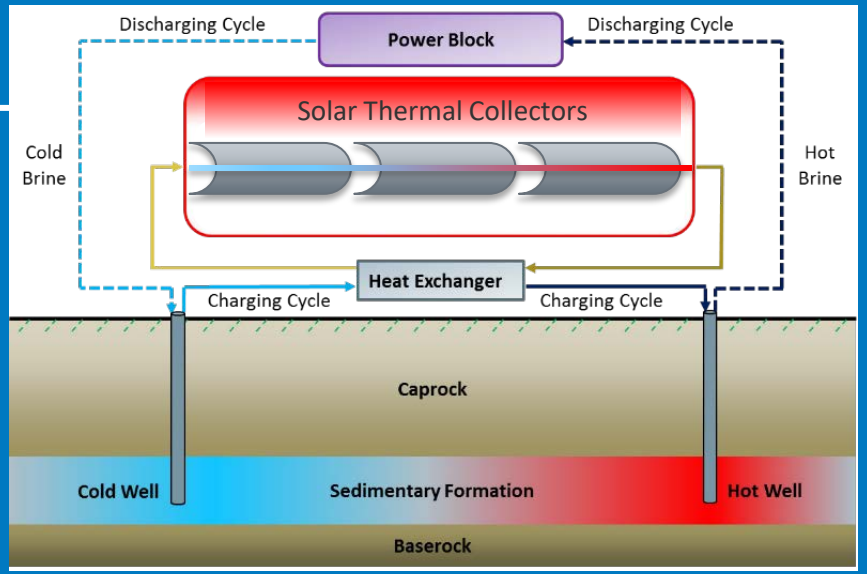


NREL's Preliminary Conclusions

- *When included in the analysis*, CSP deployments play a significant role in achieving California SB100 targets
- New CSP capacity is added in 2035 and steady growth continues through 2045
  - CSP provides 6% of installed capacity and 15% of generation in the focus area by 2045
  - Up to 9 GW_e of CSP deployed by 2045
- CSP serves as generation with 12-14 hours of energy storage
  - CSP plants generally run at 100% at night and at reduced load during the day
- CSP mainly offsets wind, PV, and battery capacity additions and generation
- CSP must solve its hot tank durability issues to be considered in future renewable deployments.

Craig Turchi, Sarah Awara, Chad Augustine, Hank Price, *U.S. Market Update: CSP Deployment Potential in California under SB100*, SolarPACES, Sydney, Australia, October 10-13, 2023.

GeoTES: Geological Thermal Energy Storage Charged with Solar Thermal Technology Using Depleted Oil/Gas Reservoirs



GeoTES Demonstration


Department of Energy

DOE Announces $33 Million to Deploy Solar Technologies to Decarbonize America's Industrial Sector

JULY 25, 2024

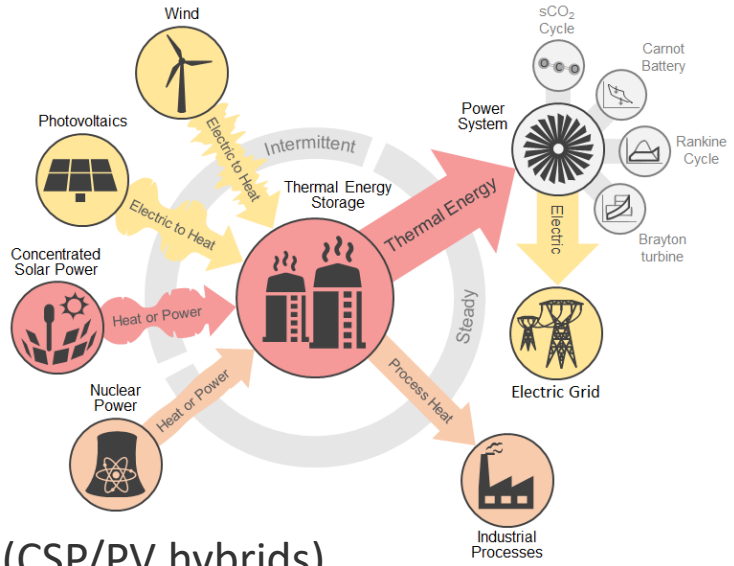
Energy.gov » DOE Announces $33 Million to Deploy Solar Technologies to Decarbonize America's Industrial Sector

Nine Projects Across Seven States Will Support Solar-Powered Production of Hydrogen and Lower Emissions from the Aviation, Food and Beverage, and Other Sectors

Premier Resource Management (Bakersfield, CA), in partnership with the National Renewable Energy Laboratory, will develop a 100-kW_e demonstration power plant with more than 12 hours of storage that stores thermal heat underground at retired fracking sites in California.
(Award Amount: $6 million)

- Stores solar thermal energy in the subsurface
- Requires solar thermal, oil & gas, and geothermal expertise
- Extends storage duration at low marginal cost, i.e., daily or seasonal storage services
- Develops techno-economic model to explore system economic: how monetize the value of the system?
- Costs are high but potential for reduction with improved system design and dispatch

Summary



- Molten salt (Gen2) CSP+TES can compete with PV+batteries when multiple hours of storage are required *if* it solves its hot tank issues.
  - All future CSP plants likely to include onsite PV (CSP/PV hybrids)
  - PV+ETES is a potential competitor to CSP+TES
  - Particle TES (e.g., sand) holds potential for higher temps and greater efficiency while avoiding known molten-salt issues
- GeoTES taps existing subsurface reservoirs, using brine for multi-week storage with low marginal cost for extended storage duration.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Thank you

www.nrel.gov

craig.turchi@nrel.gov

NREL/PR-5700-90759

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Proposed Brenda CSP Project

300 MW PV
190 MW CSP with TES

Heliogen plans to set up a Hybrid Renewable Energy facility in Brenda, Arizona. The Solar Energy Zone provides ideal conditions for concentrated solar installations, allowing Heliogen to produce low-cost, carbon-free power to meet growing demand while reducing emissions.

Meet Heliogen

Heliogen is a California-based renewable energy technology company on a mission to decarbonize industry, using concentrated sunlight and thermal energy storage to deliver carbon-free power and steam for round-the-clock operations. We are developing and commercializing our concentrating solar-thermal energy (CSP) infrastructure integrated with Solar PV and Long Duration Energy Storage (LDES).

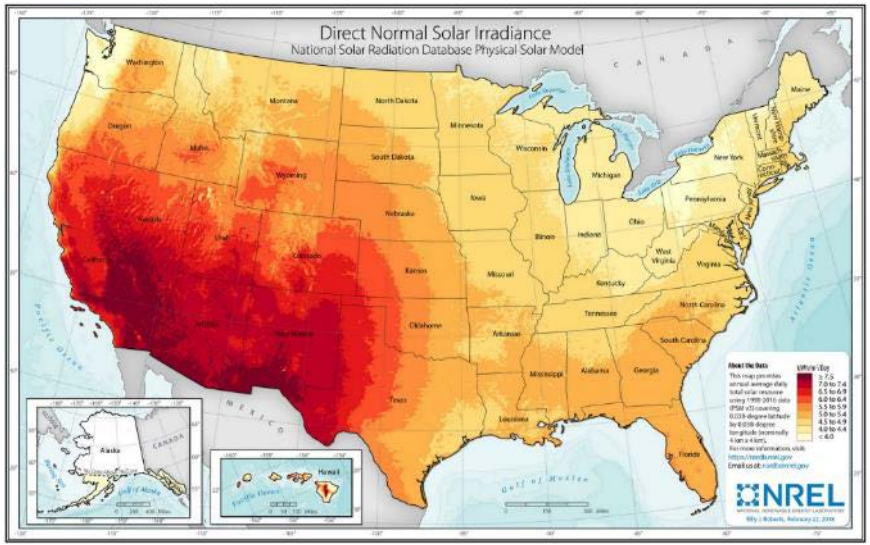
The Brenda Renewable Power Project

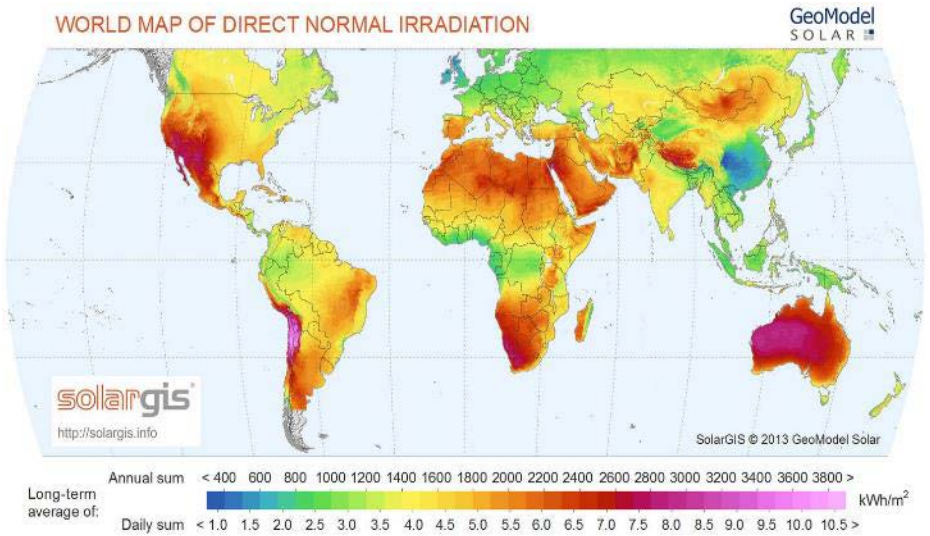
The Brenda project, located in La Paz County, Arizona, will be a clean power plant that combines concentrated solar power (CSP), solar PV, and thermal energy storage using molten salt. This "hybrid" approach of CSP+ PV + molten salt storage is already commercially mature and globally deployed at large scales.

Heliogen has secured a 30-year lease for the 3,343-acre site from the Bureau of Land Management (BLM), which has designated the site as a federal Solar Energy Zone.

https://www.heliogen.com/wp-content/uploads/2024/06/Brenda-Renewable-Power-Project_2024.pdf

Direct Normal Solar Resource





Direct sunlight is required for concentrating solar systems.