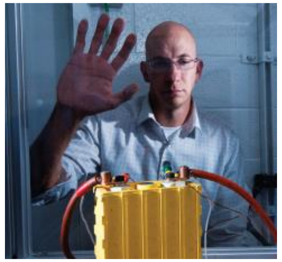
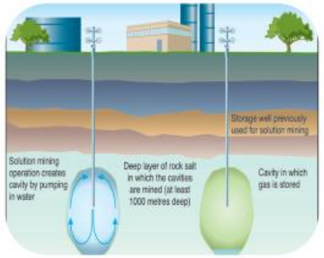
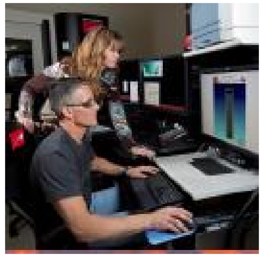
SAND2021-13001C

Presented at the 2021 TechConnect World Innovation Conference & Expo, October 18 – 20, 2021

Long-Duration High-Temperature Thermal Energy Storage for Grid and Industrial Applications







PRESENTED BY

Clifford K. Ho, Ph.D., ckho@sandia.gov

Sandia National Laboratories

SAND2021-XXXX

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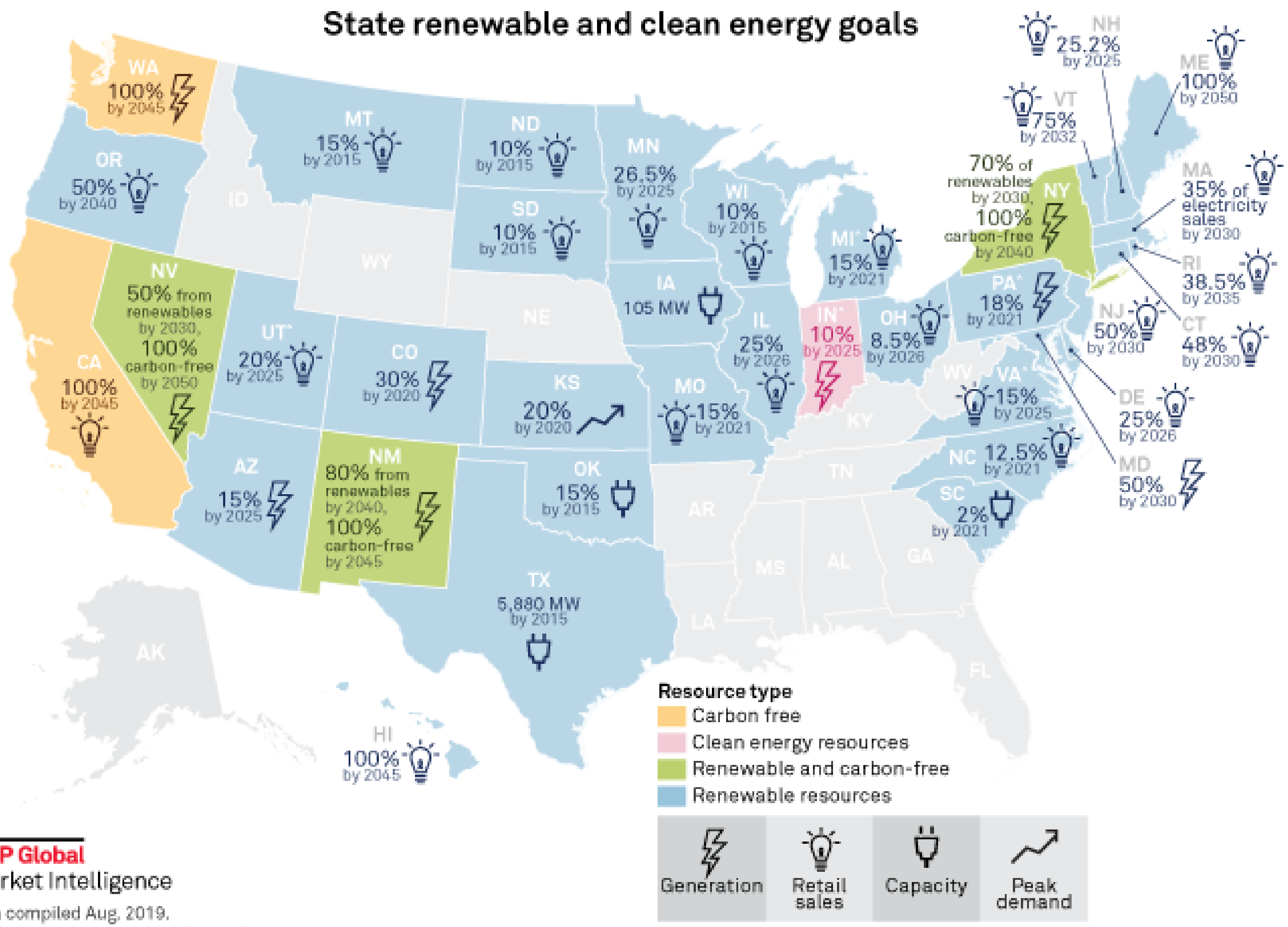
Overview

- Problem Statement
- Overview of Thermal Energy Storage for Grid Applications
- Process Heat for Industrial Decarbonization

Problem Statement

Large-capacity, long-duration energy storage solutions[1] will be needed to ensure grid performance[2] with increasing intermittent renewables

[1]LDES market is nascent
[2]Stability, reliability, resilience

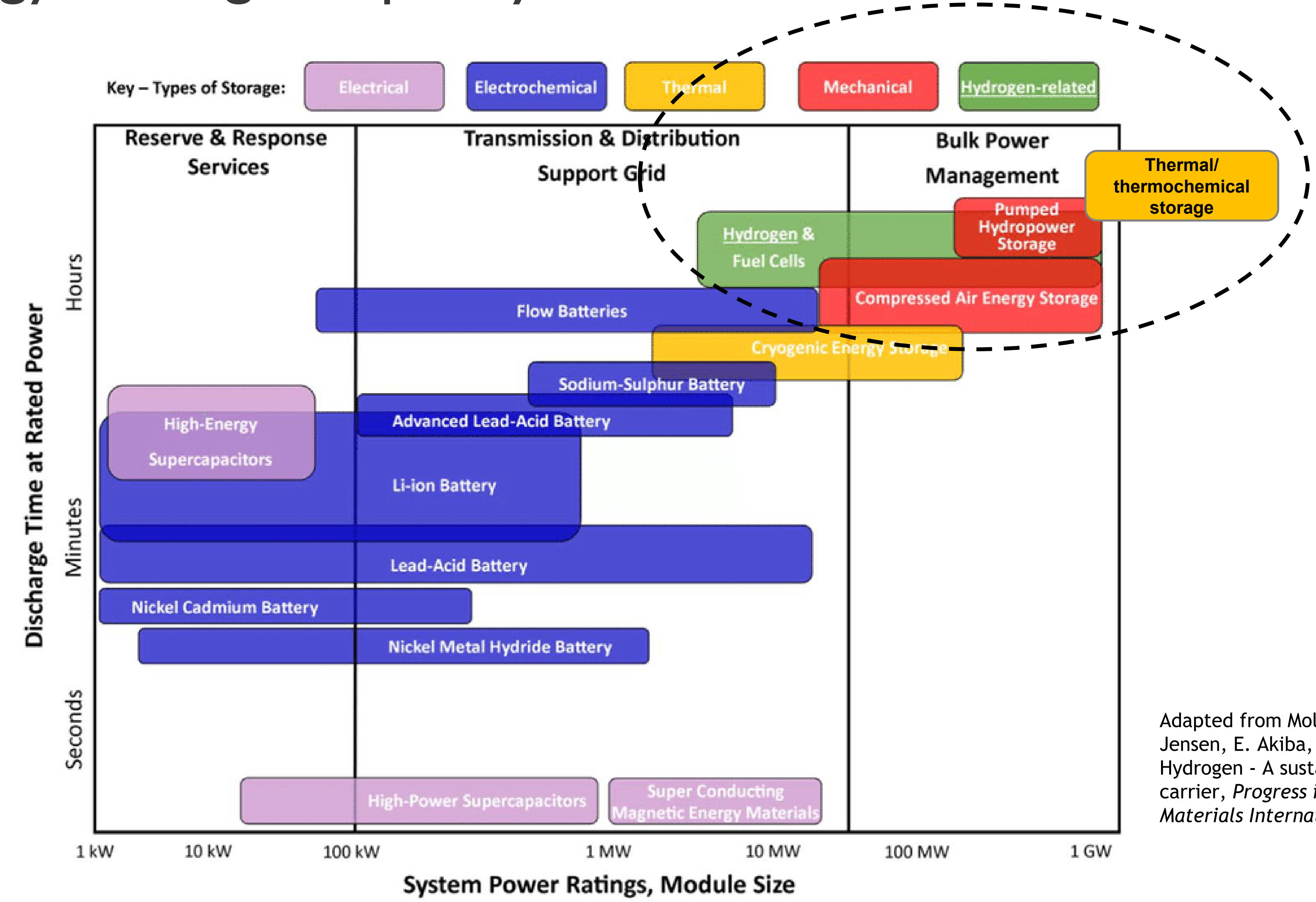


S&P Global
Market Intelligence

Data compiled Aug. 2019.
* Includes non-renewable alternative resources.
Indiana, Kansas, North Dakota, Oklahoma, South Carolina, South Dakota, Utah and Virginia have renewable portfolio goals instead of standards.
Virginia's RPS goal is based on the volume of electricity sold in 2007.
Map credit: Ciaralou Agpalo Palicpic
Sources: S&P Global Market Intelligence; Sierra Club; Union of Concerned Scientists; Database of State Incentives for Renewables & Efficiency; and state public utility commission websites

https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-states-face-uneven-paths-in-movement-for-100-clean-energy-53419260

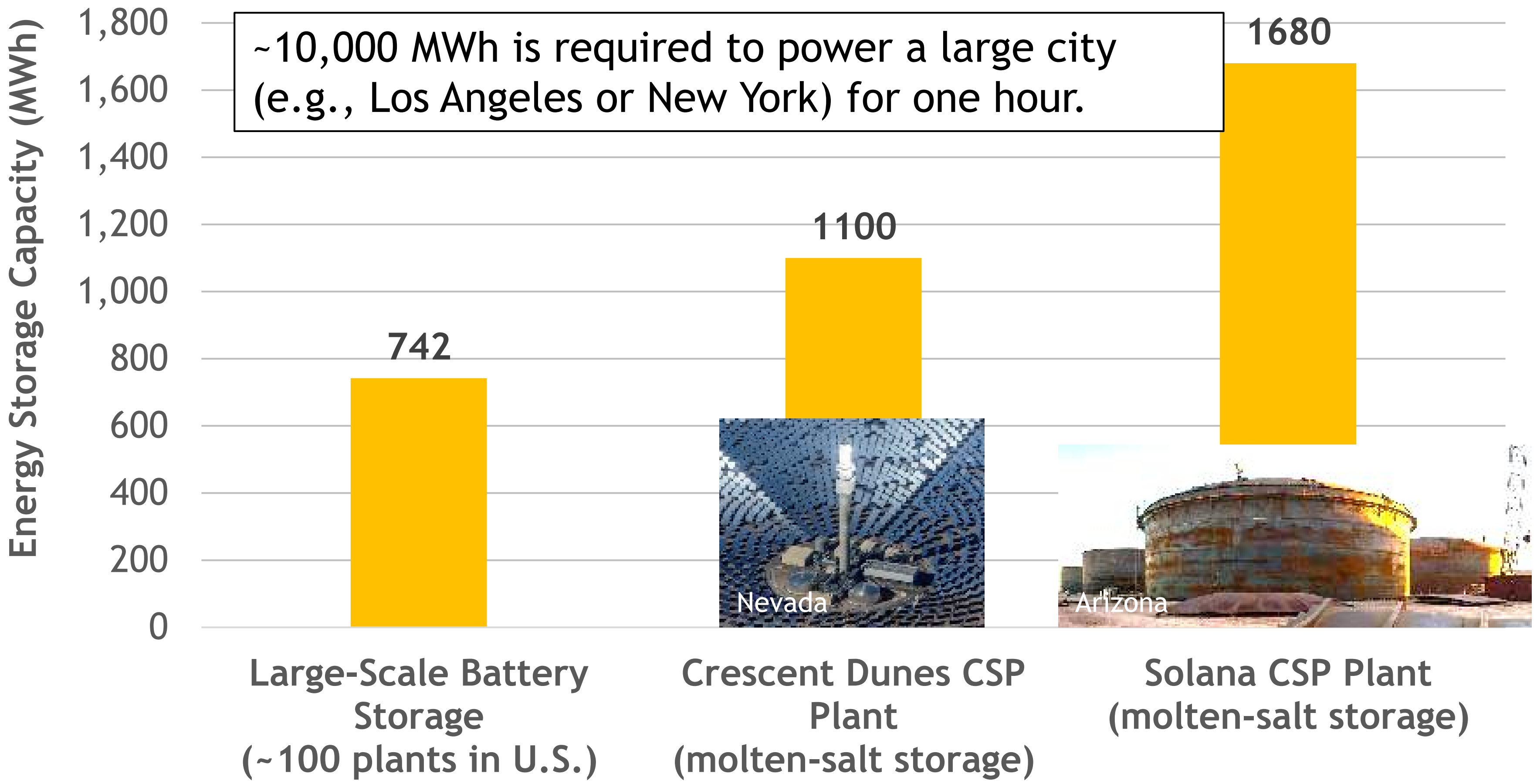
Energy Storage Capacity and Duration



Adapted from Moller, K.T., T.R. Jensen, E. Akiba, and H.W. Li, 2017, Hydrogen - A sustainable energy carrier, *Progress in Natural Science-Materials International*, **27**(1), p. 34-40

Li-Ion vs. Thermal Energy Storage Capacity

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



CSP = concentrating solar power

Overview

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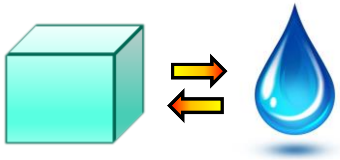
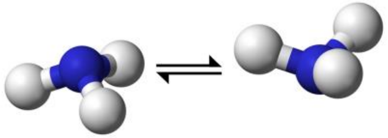
- Process Heat for Industrial Decarbonization

Thermal Energy Storage - Overview

- 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

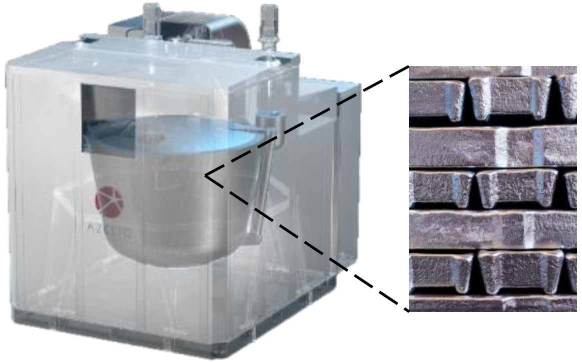


- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)



- Thermochemical storage
  - Converting thermal energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)

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

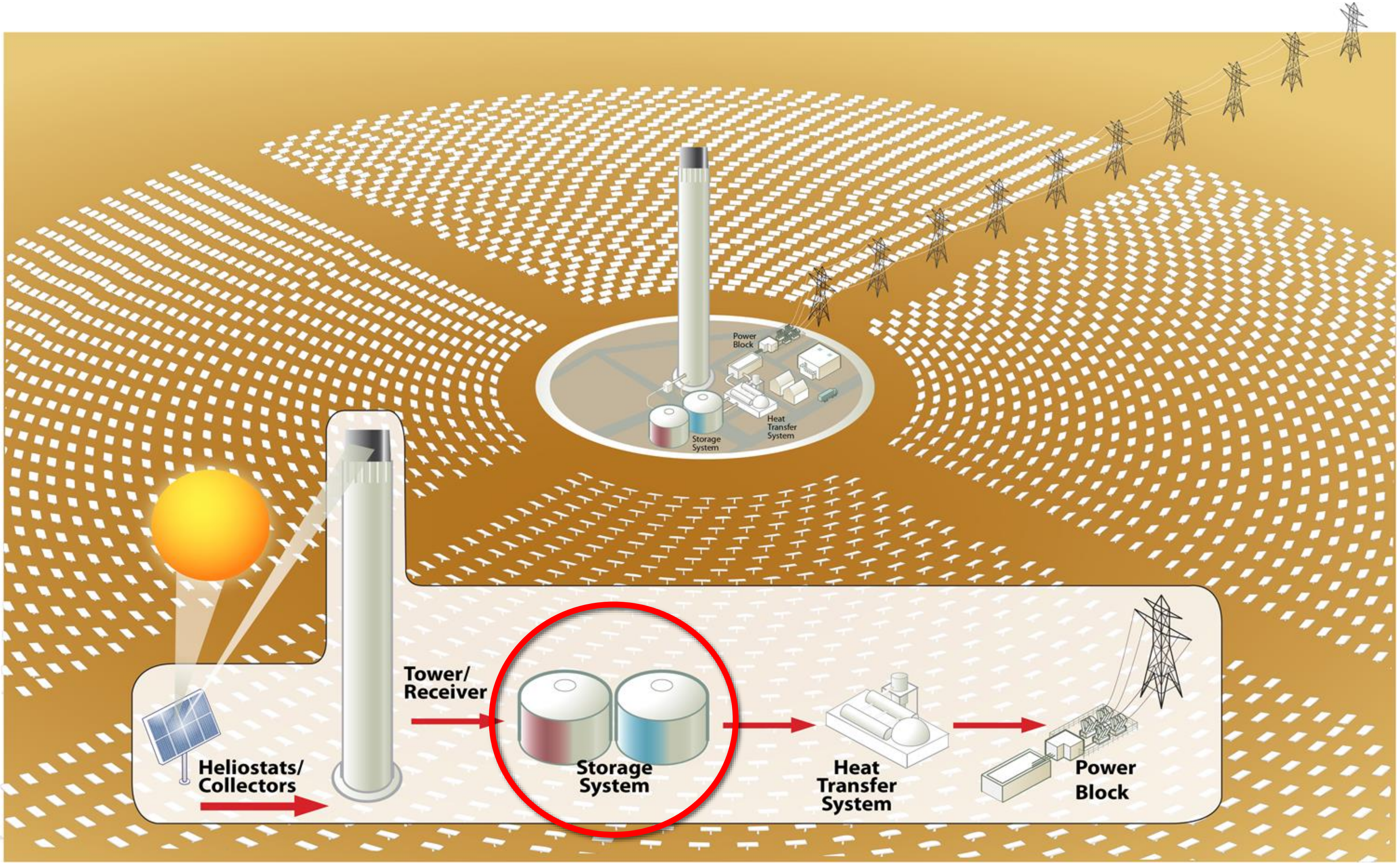


Azelio
Molten Aluminum Alloy Phase Change

https://www.sandia.gov/ess-ssl/wp-content/uploads/2021/LDES/Torbj%C3%B6rn_Lindquist.pdf

Molten-Salt Thermal Storage

Concentrating Solar Power and Thermal Energy Storage



Molten Salt Storage with CSP

- Nearly 30 GWh_e of global capacity using concentrating solar power (CSP)

futurenergyweb.es

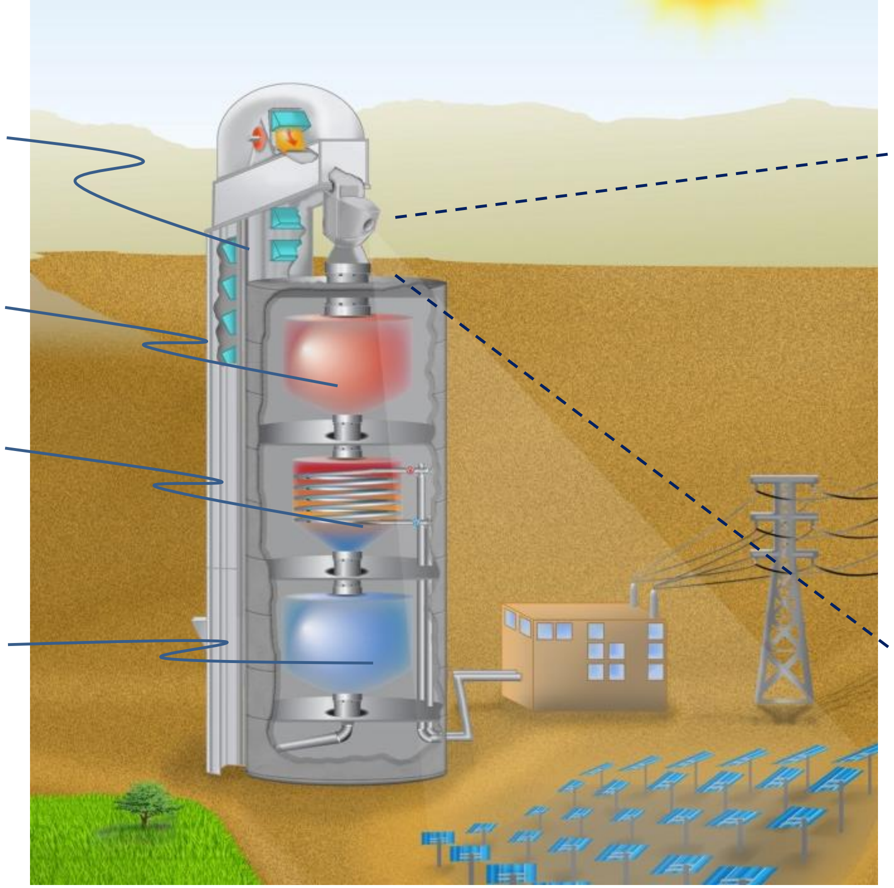
Solana Parabolic Trough Plant, AZ
(280 MW_e with 6 hrs storage (1.5 GWh_e)

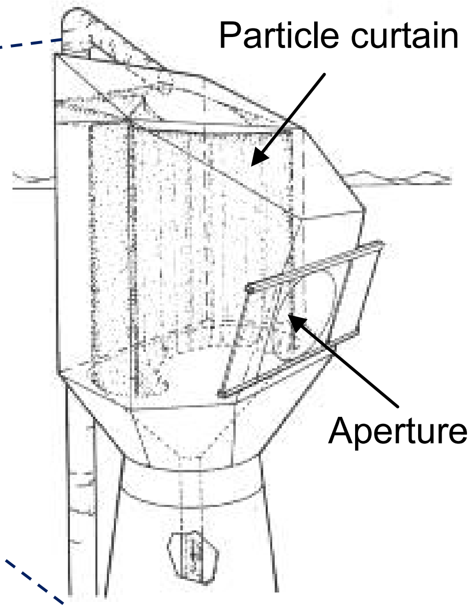
Crescent Dunes Solar Tower, NV
110 MW_e with 10 hrs storage (1.1 GWh_e)

Moving Particle Thermal Storage

Moving Particle Thermal Storage with CSP

High-Temperature Particle-Based CSP





Falling particle receiver

Moving Particle Thermal Storage with CSP

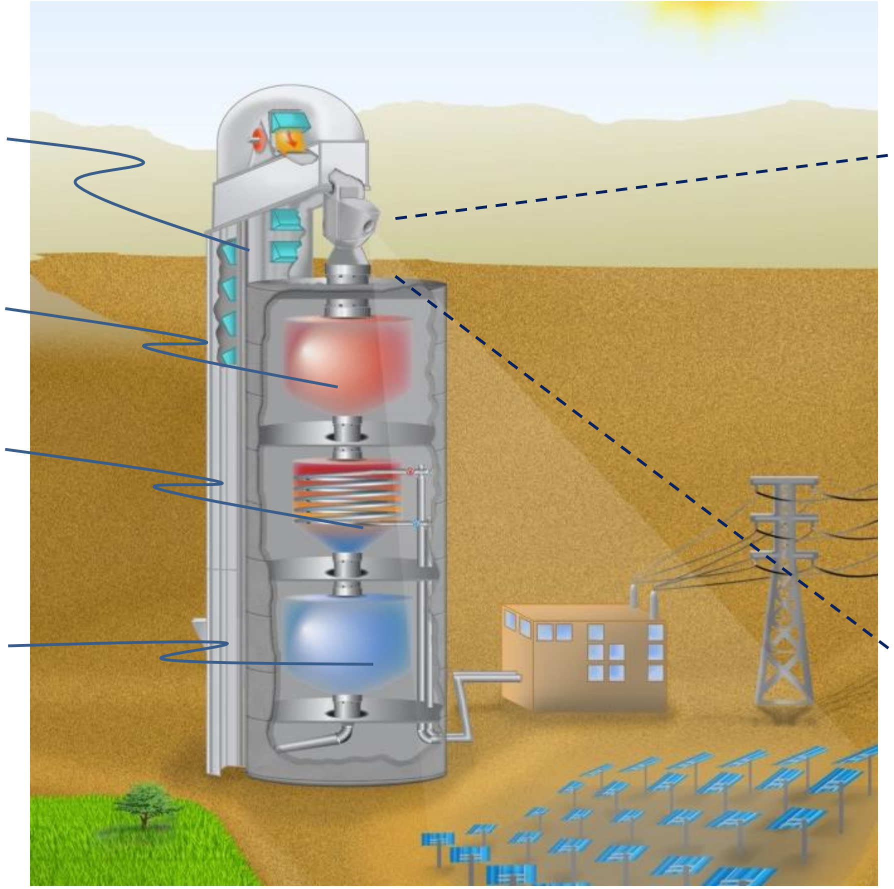
High-Temperature Particle-Based CSP

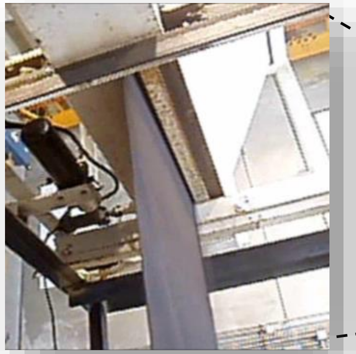
Particle elevator

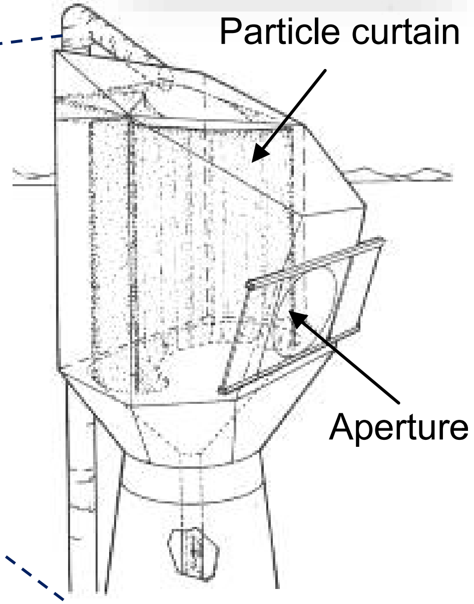
Particle hot storage tank

Particle-to-working-fluid heat exchanger

Particle cold storage tank





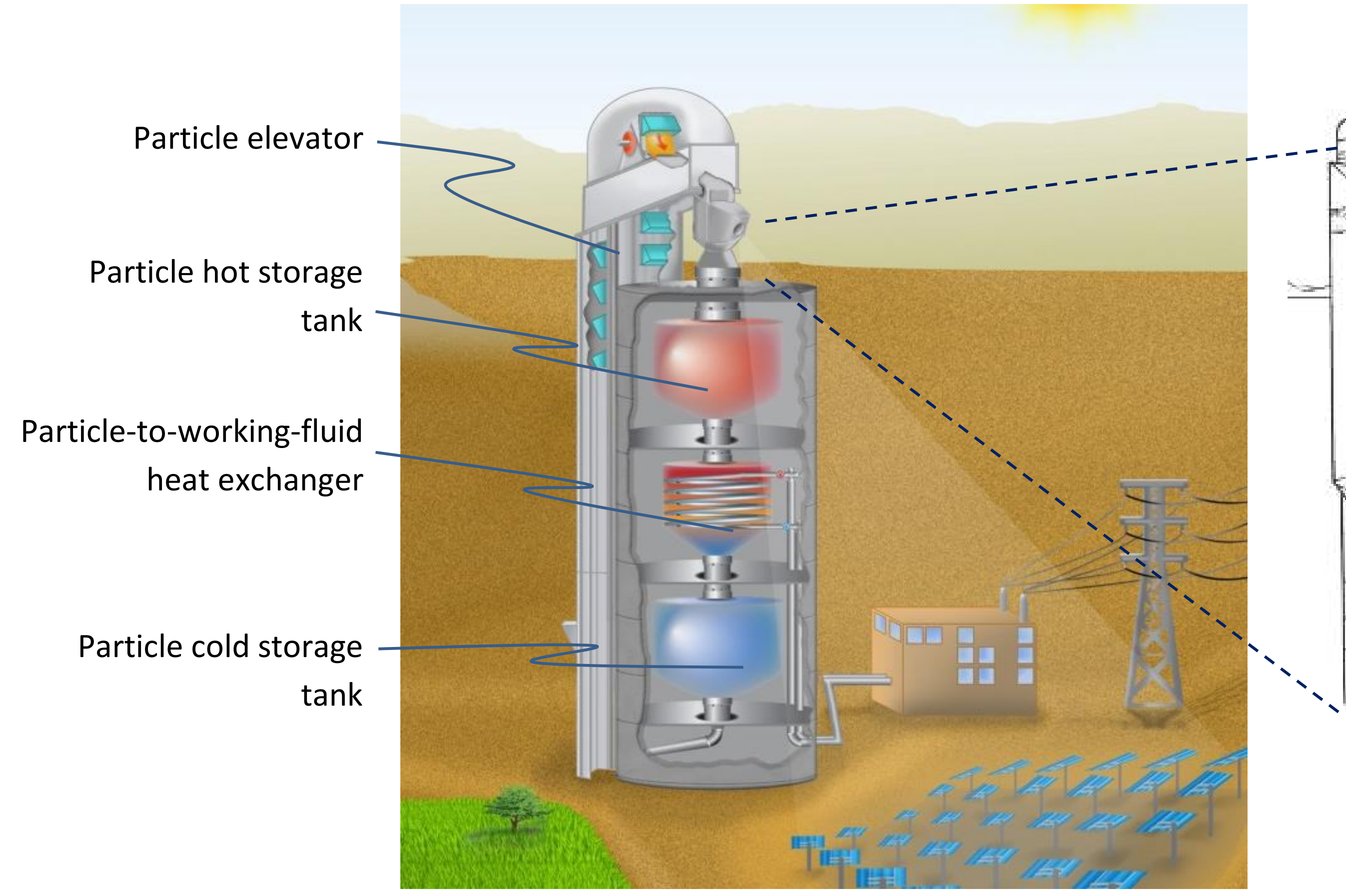


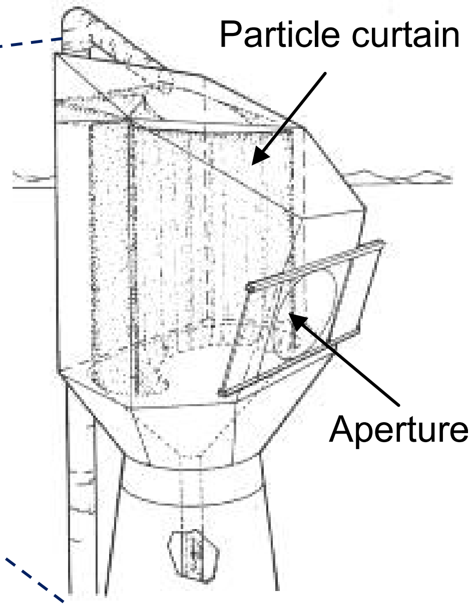
Falling particle receiver

National Solar Thermal Test Facility
Sandia National Laboratories

Moving Particle Thermal Storage with CSP

High-Temperature Particle-Based CSP



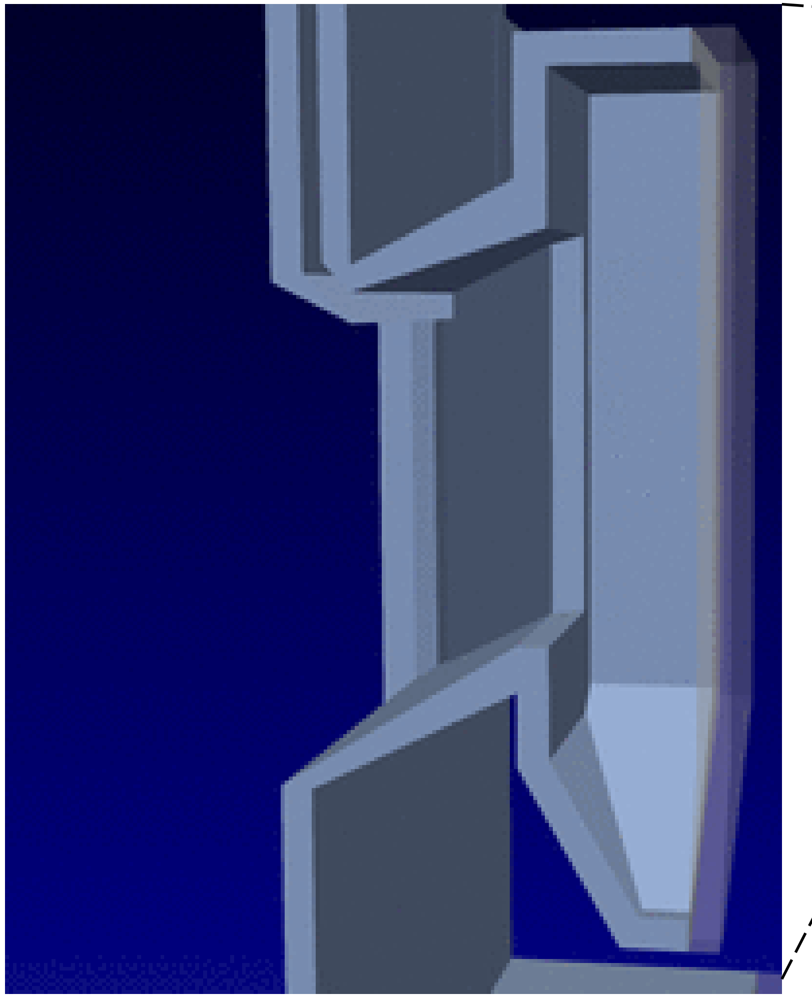


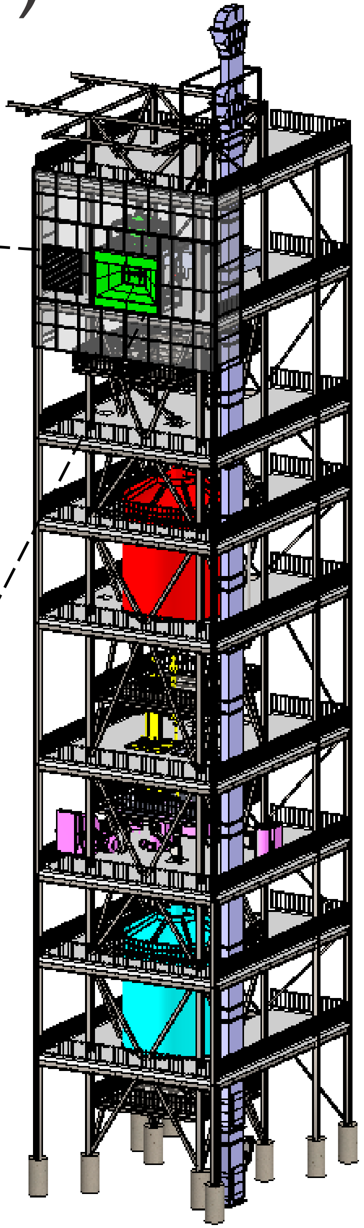
Falling particle receiver

- Higher temperatures (>1000 °C) than molten nitrate salts
- Direct heating of particles vs. indirect heating of tubes
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles

Gen3 Particle Pilot Plant (Sandia)

Next-Generation High-Temperature Falling Particle Receiver





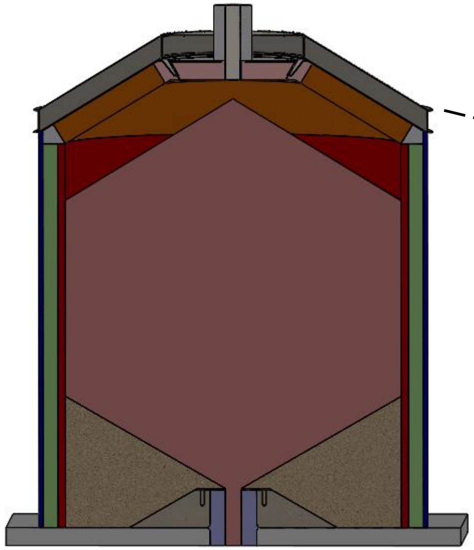
K. Albrecht, SNL

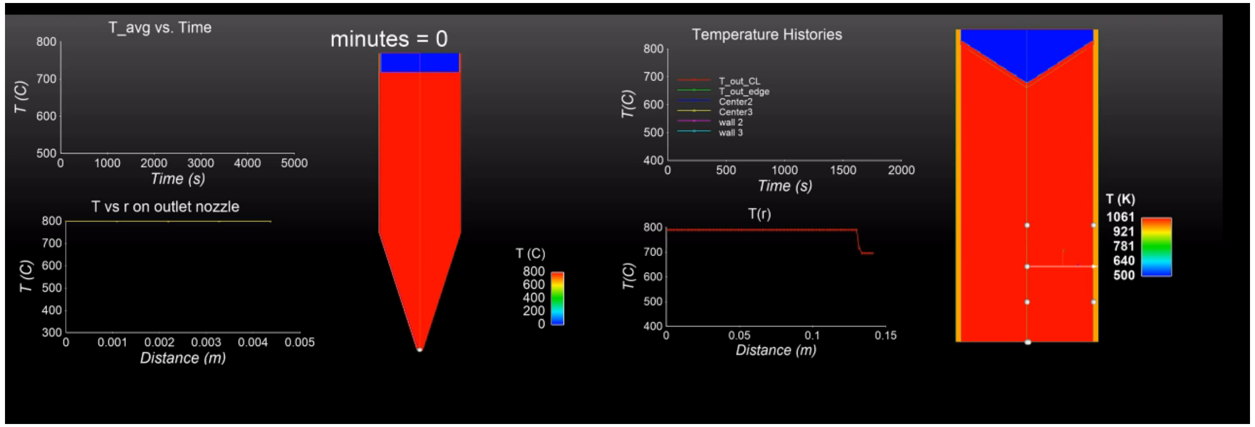
Gen 3 Particle Pilot Plant

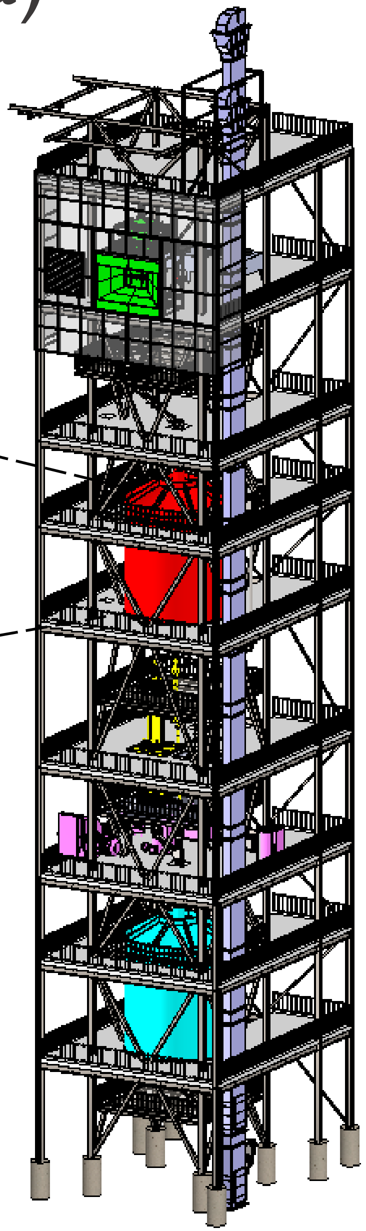
- ~1 – 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 – 400 micron ceramic particles (CARBO HSP 40/70)

Gen3 Particle Pilot Plant (Sandia)

High-Temperature Particle Storage Bin
(Allied Mineral Products, Matrix PDM, Sandia)







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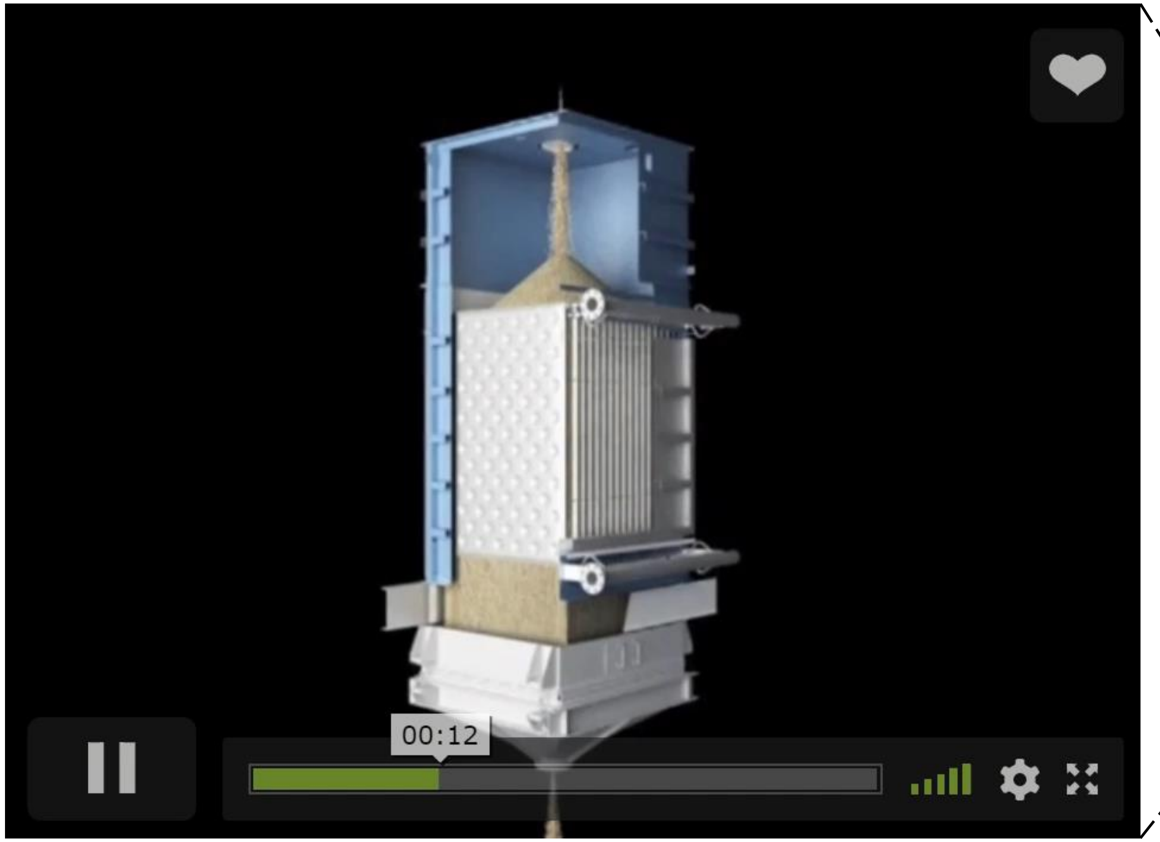
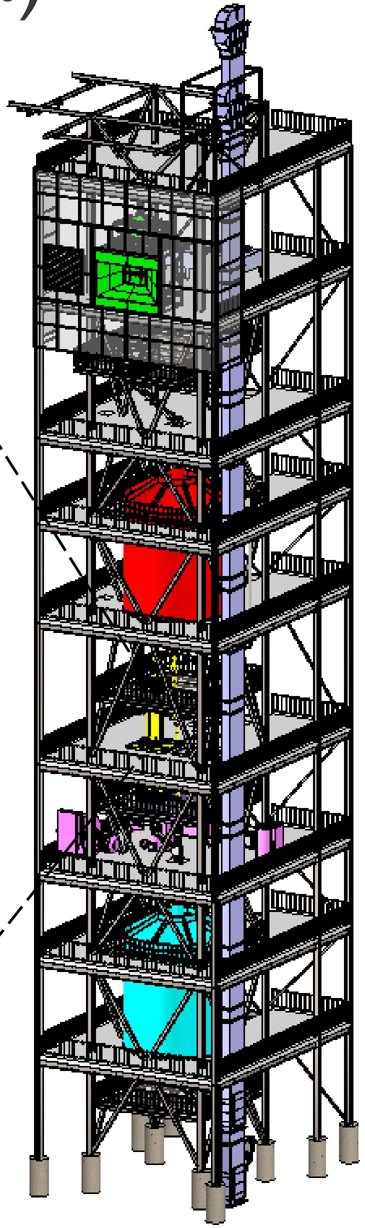
K. Albrecht, SNL

Gen3 Particle Pilot Plant (Sandia)

High-Temperature Particle-to-sCO_2 Heat Exchanger
(VPE, Solex, Sandia)



https://www.solexthermal.com/our-technology/cooling/



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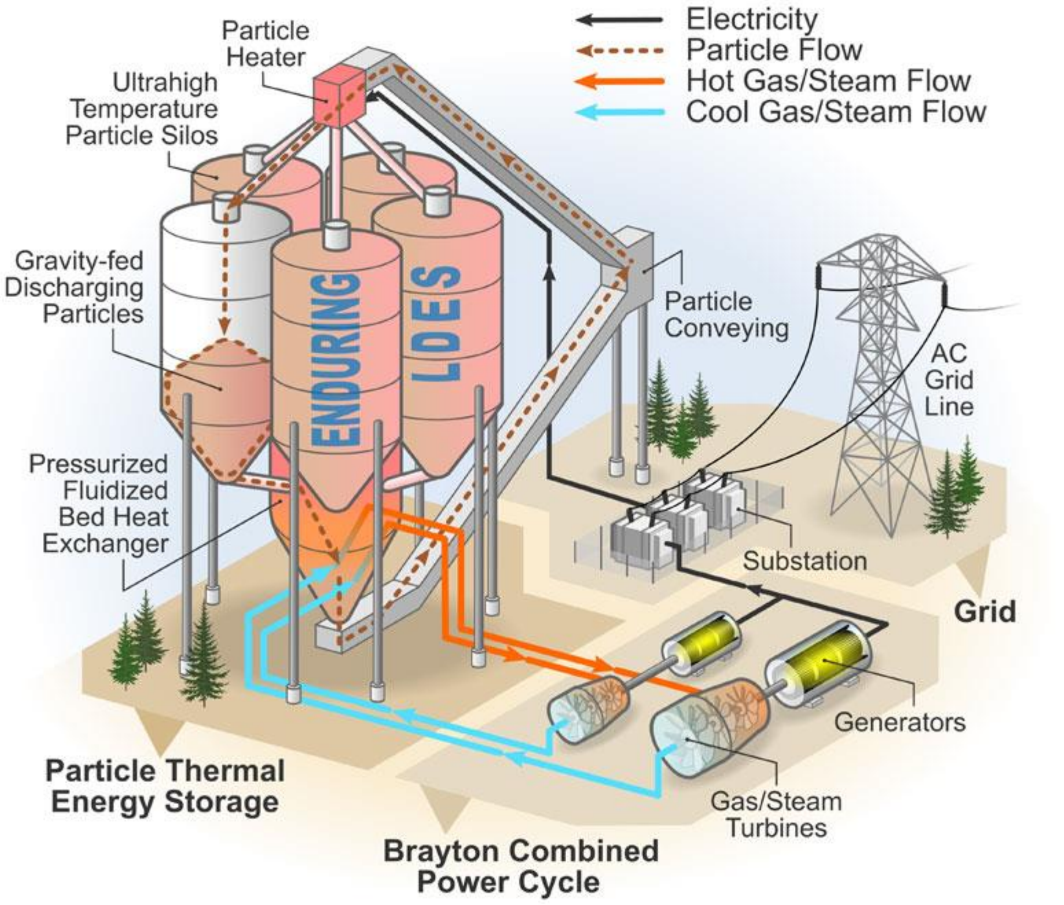
K. Albrecht, SNL

NREL (Z. Ma) – Moving Particle Thermal Storage

"ENDURING" Long Duration Energy Storage – ARPA-E DAYS program

Electrical resistive heating of moving particles



https://www.nrel.gov/news/program/2021/nrel-options-a-modular-cost-effective-build-anywhere-particle-thermal-energy-storage-technology.html

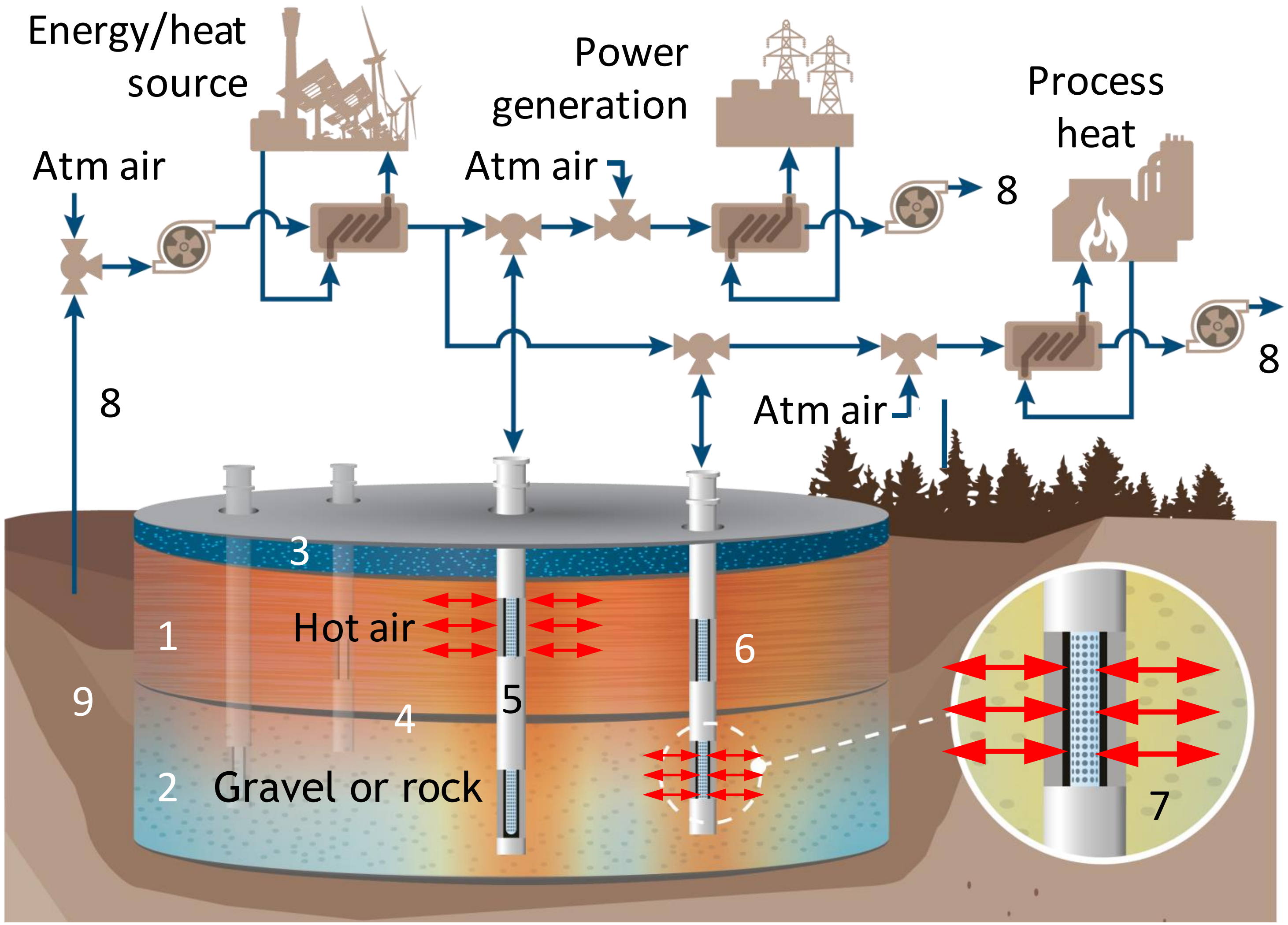
Fixed-Bed Thermal Storage

Solid Particle Storage – Fixed Bed

Siemens Gamesa Electric Thermal Energy Storage pilot demonstration with thermal storage capacity of 130 MWh at temperatures of 750 °C (image from website).

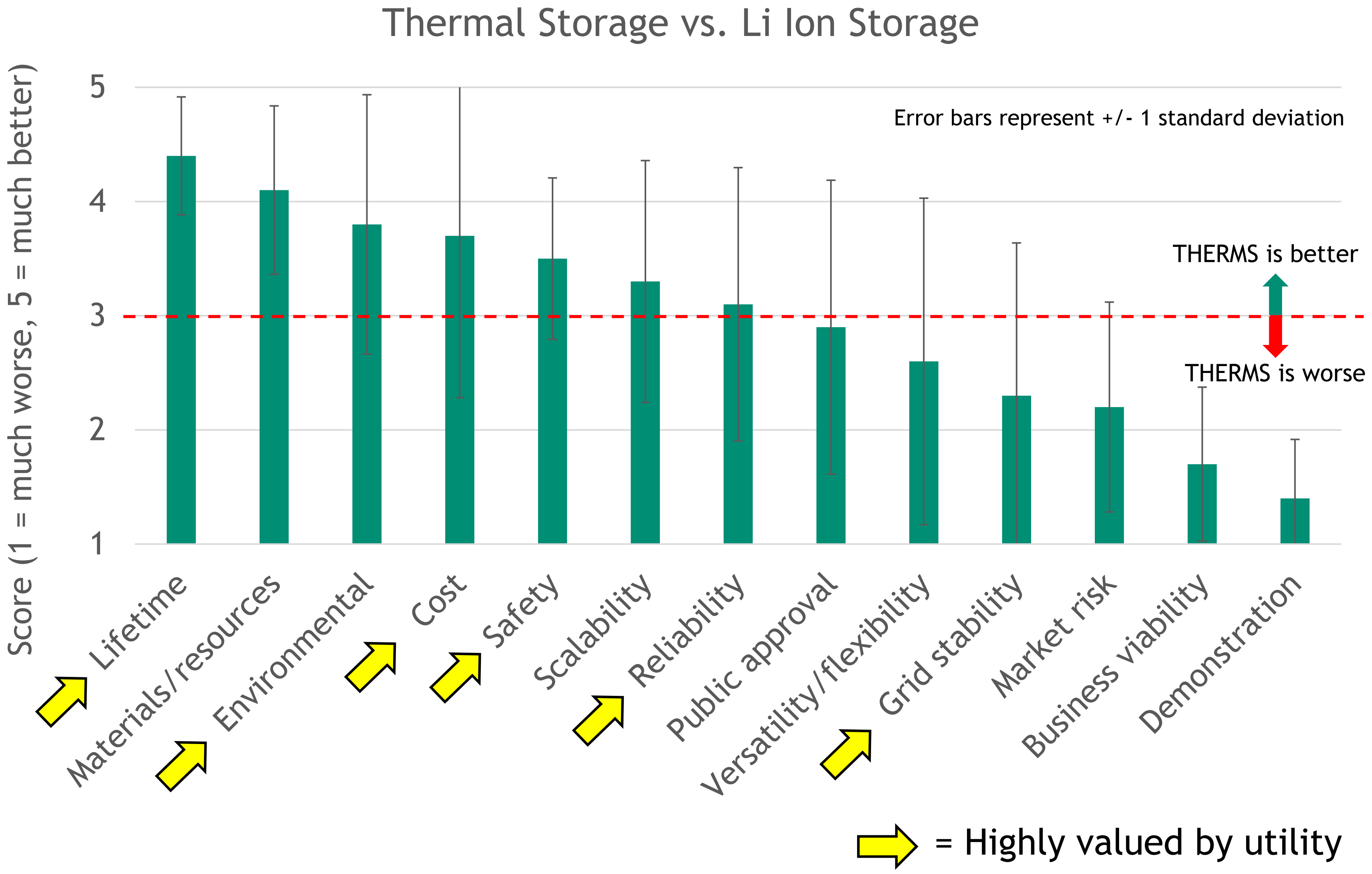
THERMS – Terrestrial Heat Repository for Months of Storage

NM Small Business Assistance Program with CSolPower, 2020
DOE Energy I-Corps, Cohort 12, Team 137 (March – May, 2021; C.Ho, H. Laubscher, K. Guin, S. Willard, G. Ho)



THERMS provides low-cost, large-capacity, **long-duration energy storage** for a **carbon-free electrical grid** and high-temperature **process heat.**

Customer Discovery – Needs / Pain Points



90 Interviews

8minute Solar Energy
Aalborg
Ait Baha
Ait Baha project involvement : AIL SA
Ambri
Arizona Public Service Company (APS)
Augwind Energy
Azelio
BloombergNEF
Bokpoort CSP
Bokpoort CSP plant
CA Energy Commission
California Energy Commission
California Energy Commission
California Energy Storage Alliance
California Public Utilities Commission
DigSilent
Echogen Power Systems
EDF Renewables -- Noor Midelt
El Paso Electric
Energy Nest
Energy Vault
Engineer at PNM (electric utility)
EPRI - Program manager
EPRI - Technical Leader in Energy Storage and Distributed Generation
ERCOT
ERCOT
Evolving Energy
Form Energy
Form Energy
Form Energy
Form Energy
Fraunhover ISE Chile
GE
GE Renewable Energy
GE Renewable Energy
GE Research
GMEC -GN Power
GNPower
Heliogen
HelioHeat
Highview Power
ISO-New England
ISO-New England
ISO-New England
JEA
Karoshoek Solar Farm
LADWP- Los Angeles Department of Water and Power
Largo Clean Energy
Largo Clean Energy
Largo Clean Energy
Maine - Office of the Public Advocate
Malta Inc
National Grid
NERC
NREL - Group Manager, Distributed Systems and Storage Analysis
NREL - LA100 report
NYSERDA
NYSERDA
NYSERDA
Omaha Public Power District
Oregon Public Utility Commission
PG&E
PNM -- Project Manager within Generation Development
PNM (Public Service Company of New Mexico)
PNM (Public Service Company of New Mexico)
PNNL
PUC Nevada
ReNew Power
Retired - AEP Distribution
Rondo Energy
Rondo Energy
Shell International Exploration & Production (US) Inc.
Solar Dynamics LLC
Southern Company
Southern Company Services, Inc.
Southern Research
Stellenbosch rockbed research
Susan Chamberlin contacts
Texas Wind Tower
Trane Technologies
TVA - Tennessee Valley Authority
U.S. Department of Energy
Urban Electric Power, Inc.
US DOE
US DOE
Utah Governor's Office of Energy Development
Vast Solar
Virginia Department of Mines, Minerals and Energy
WindSoHy

Customer/Market Discovery (DOE Energy I-Corps)

Electric utilities & all thermoelectric power plants	• Coal • Natural gas • Nuclear

Thermoelectric plants close to retirement	• Save costs on existing infrastructure
	  • Turbomachinery
	  • Steam generation
	  • Transmission

Coal plants close to retirement with useful life	• Coal plants operate at temperatures in THERMS sweet spot (~600 °C) • Access to low-cost renewable electricity for charging THERMS

TAM = Total Available Market
SAM = Serviceable Available Market
SOM = Serviceable Obtainable Market

Customer Discovery – Use Case for THERMS+

Replace burning of coal with "dirt-cheap" heat storage in the ground

Coal plant image source: https://www.power-technology.com/comment/us-clean-coal-research/

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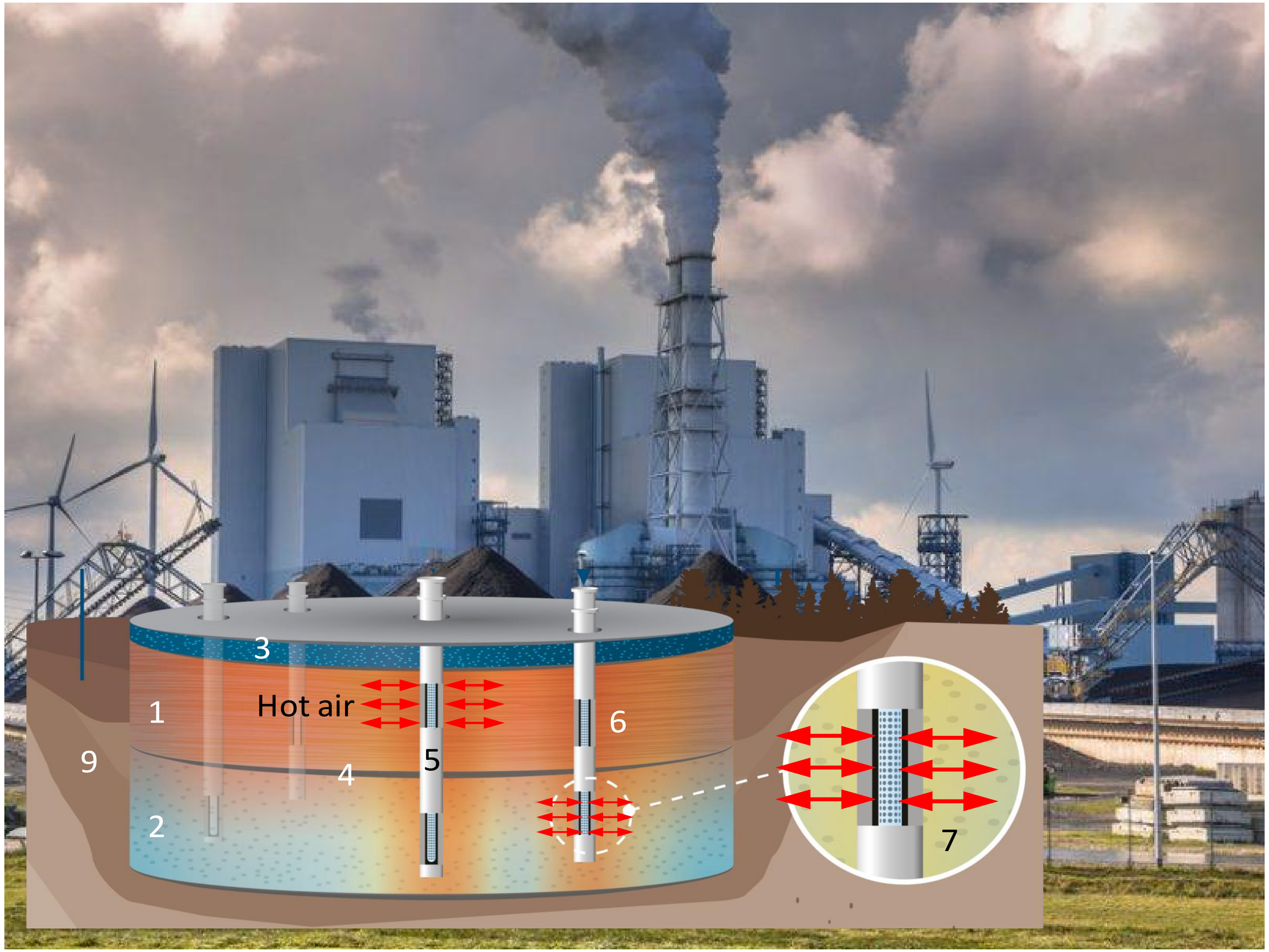

Coal plant image source: https://www.power-technology.com/comment/us-clean-coal-research/

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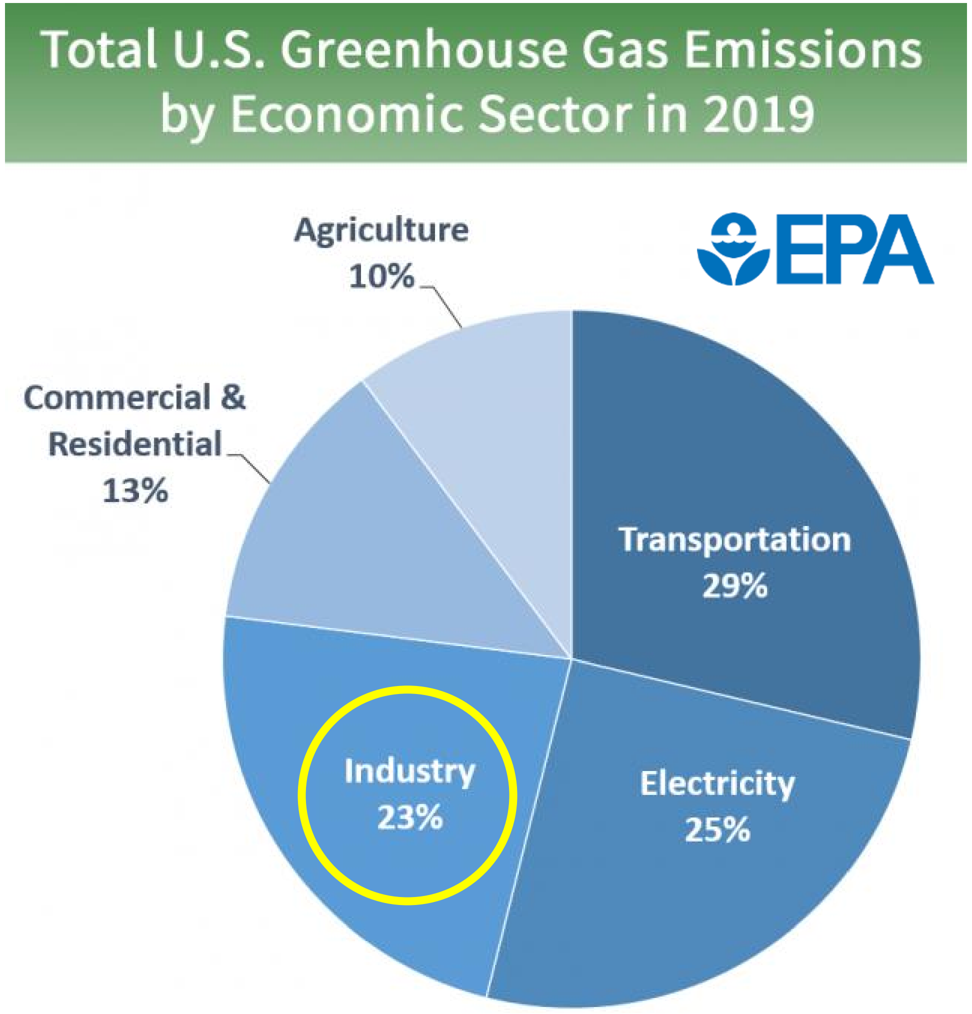
Industrial Decarbonization



Total U.S. Emissions in 2019 = 6.6 billion metric tons of CO_2 equivalent.

https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Nearly a quarter of all greenhouse gas emissions in the U.S. are from Industrial Processes and Manufacturing

Cement and steel production

Food processing and drying

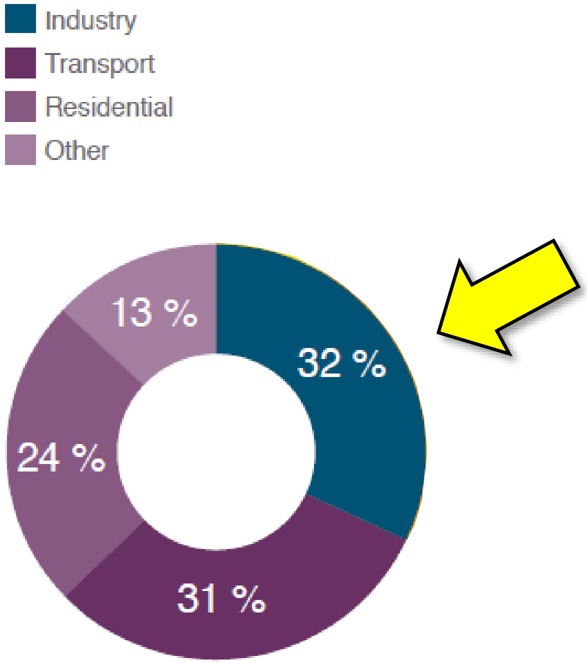
Chemicals

Electrification/automation

Petroleum refining

Untapped Potential for Industrial Heat

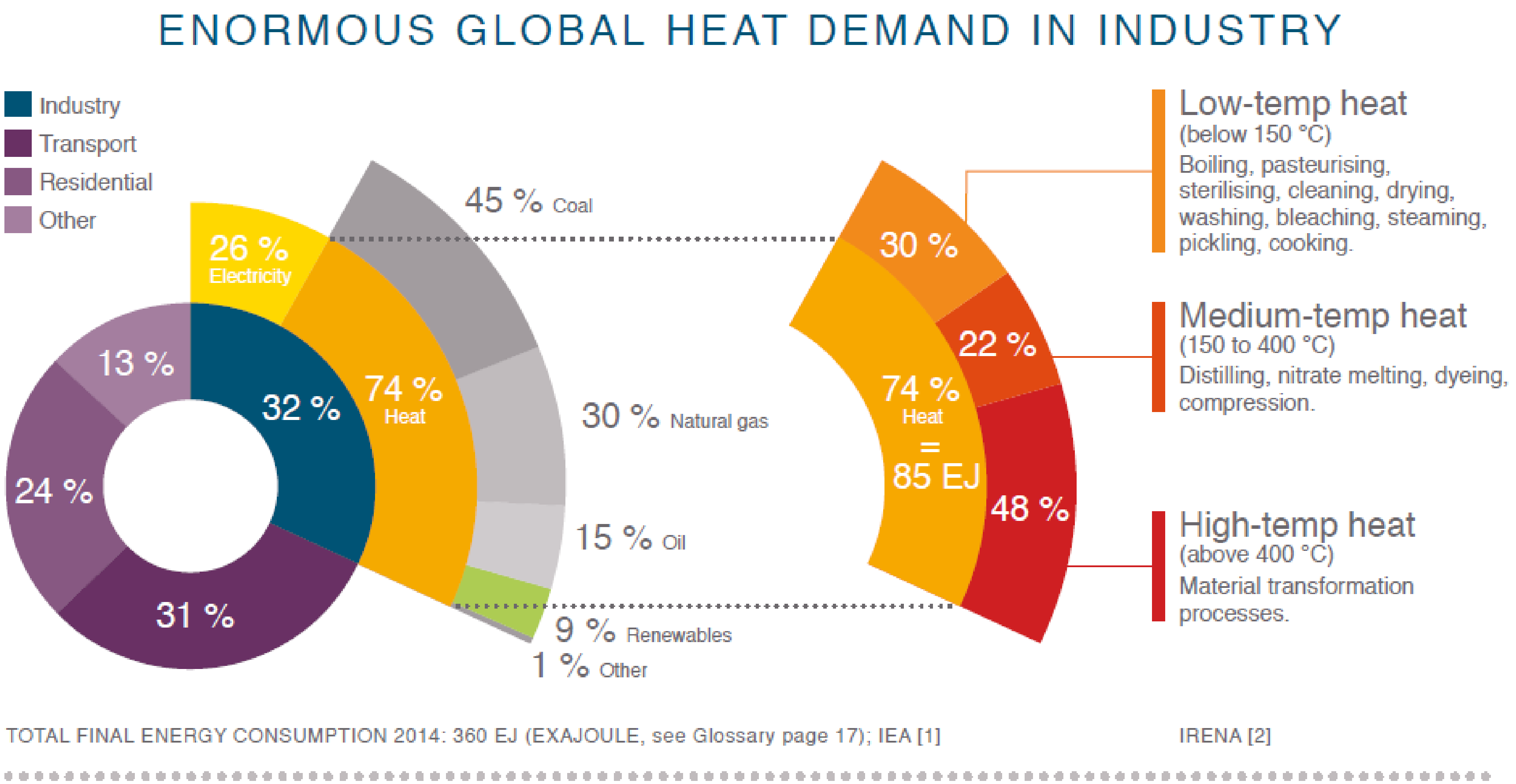
ENORMOUS GLOBAL HEAT DEMAND IN INDUSTRY



TOTAL FINAL ENERGY CONSUMPTION 2014: 360 EJ (EXAJOULE, see Glossary page 17); IEA [1]

Source: Solar Heat for Industry (2017), www.solar-payback.com
[4] European Solar Thermal Industry Federation (ESTIF), Solar Heat for Industrial Process Heat – a Factsheet, www.estif.org

Untapped Potential for Industrial Heat



Source: Solar Heat for Industry (2017), www.solar-payback.com
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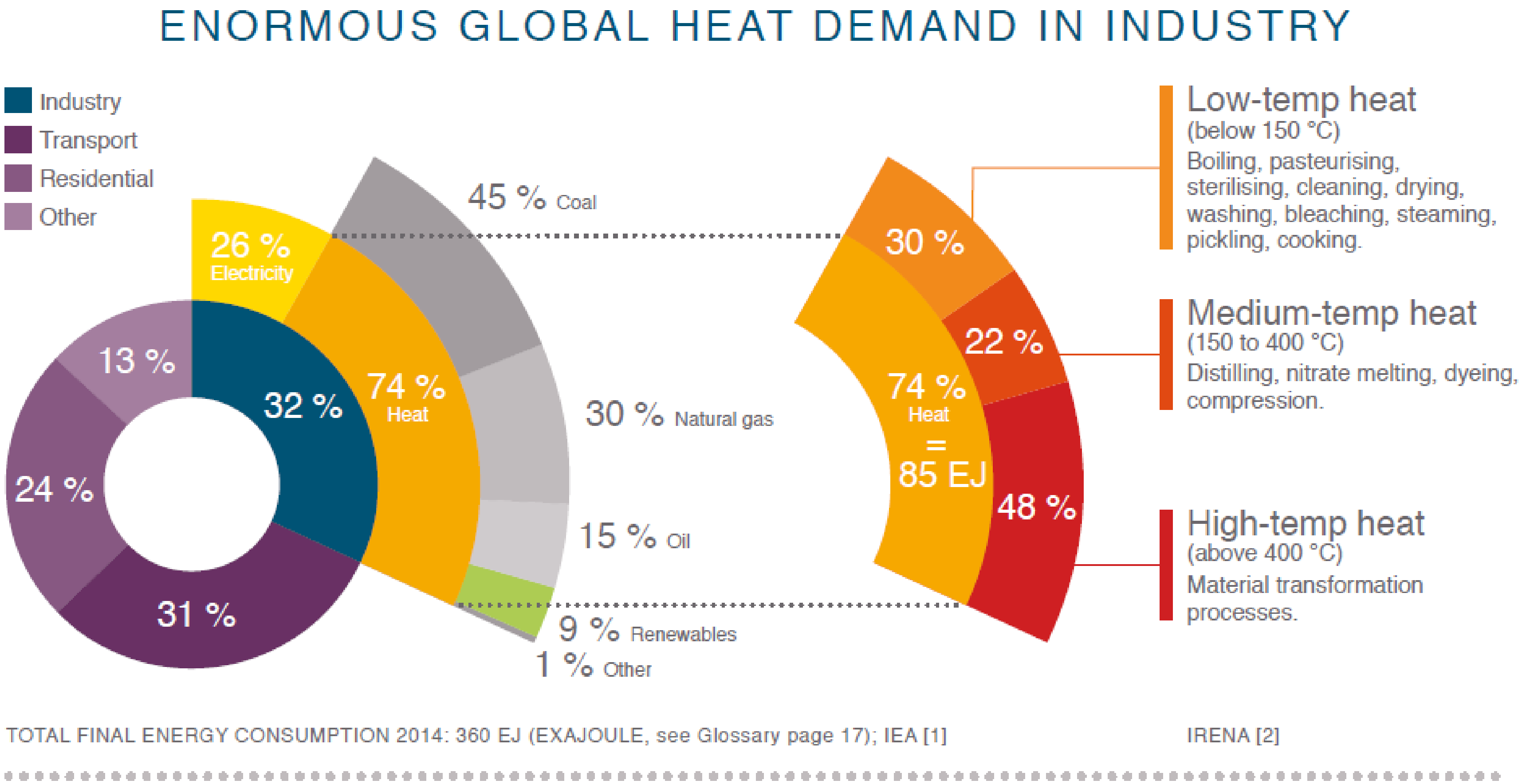
Untapped Potential for Industrial Heat



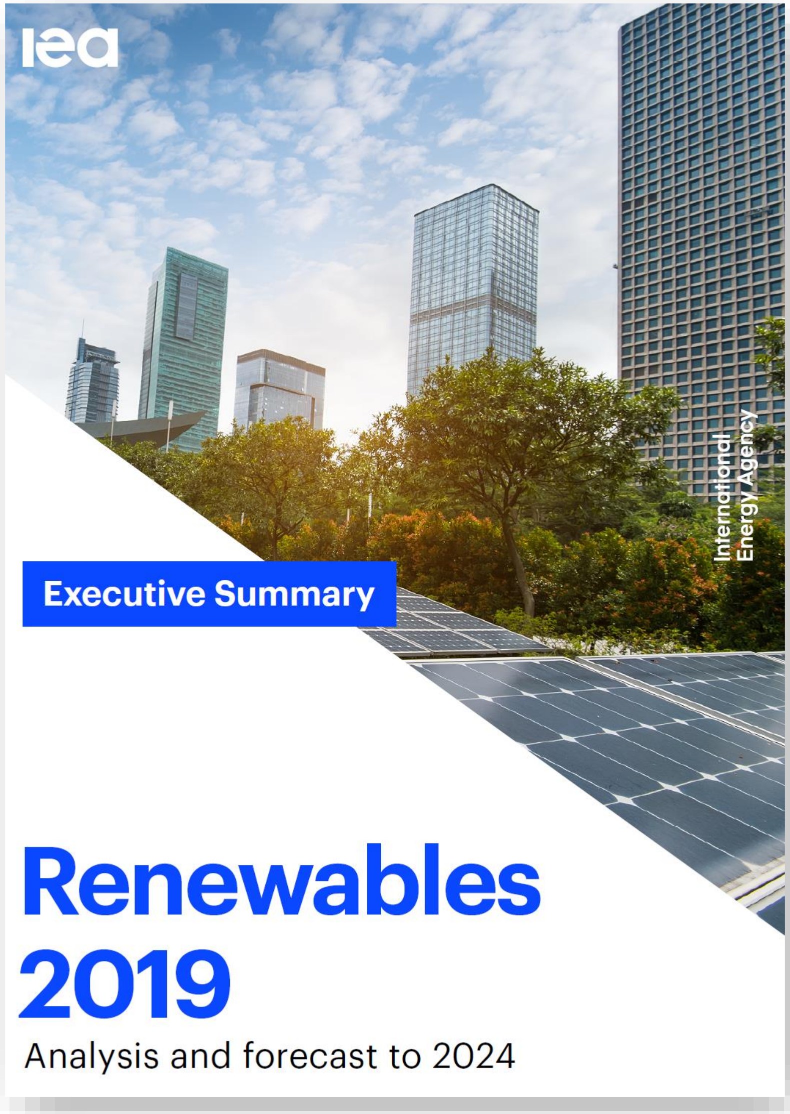
INDUSTRIAL HEAT DEMAND ON THE RISE

1.7 %

Average annual growth of industrial heat demand until 2030 [4]

Source: Solar Heat for Industry (2017), www.solar-payback.com
[4] European Solar Thermal Industry Federation (ESTIF), Solar Heat for Industrial Process Heat – a Factsheet, www.estif.org

Untapped Potential for Industrial Heat



"Overall, renewable heating potential remains vastly underexploited and deployment is not in line with global climate targets, calling for greater ambition and stronger policy support."

-International Energy Agency
https://webstore.iea.org/renewables-2019

Summary

Summary

- **Thermal storage** technologies can provide **long-duration energy storage** (GWh) – **market is nascent**
- **Moving particles** and **fixed-bed storage** (**CSP** and **electrical heating**)
  - Very low cost, "dirt cheap"
- Untapped potential to address **industrial decarbonization**
  - High-temperature **process heat**
    - Hydrogen
    - Solar thermal
    - Electrification

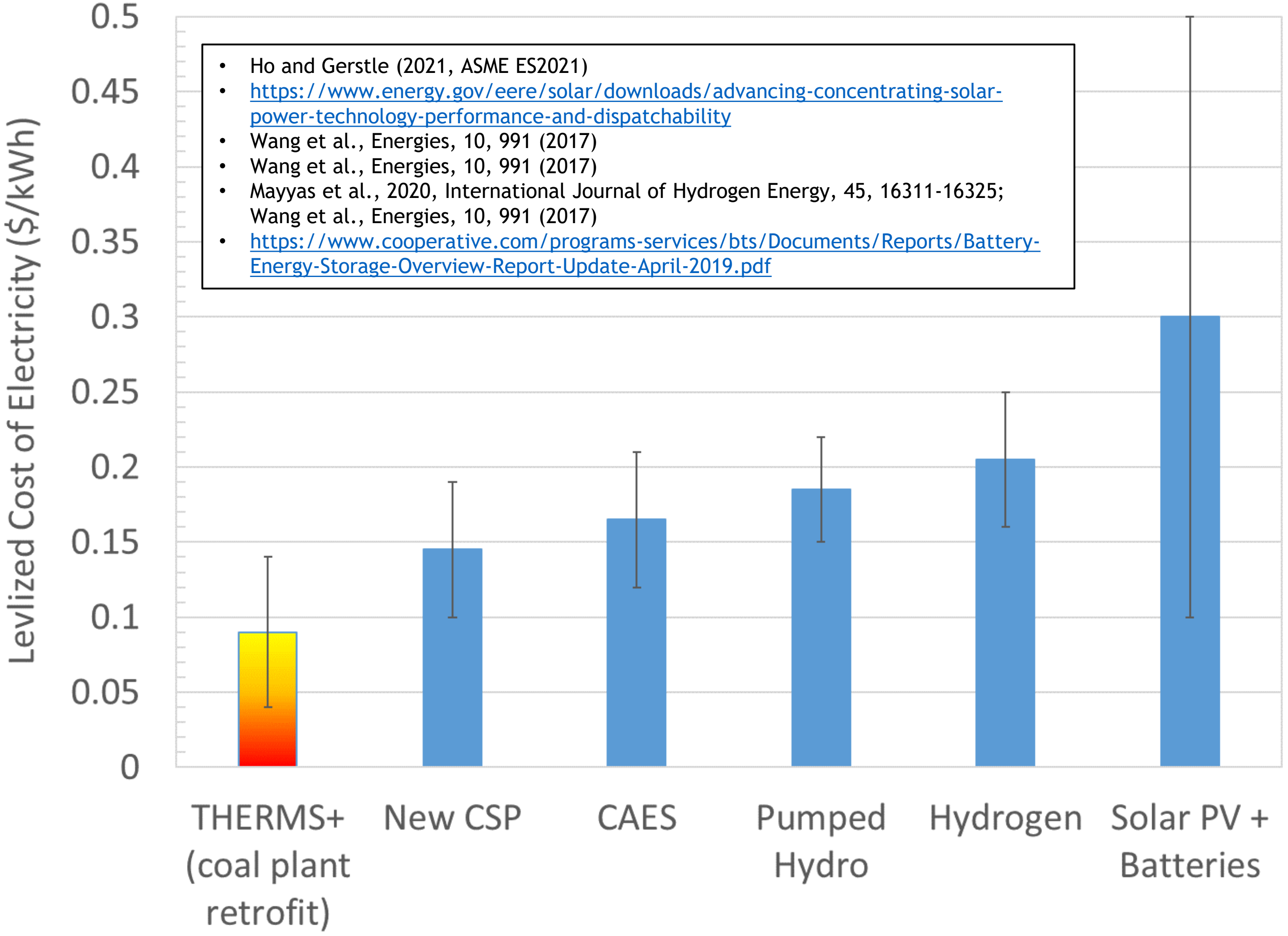
Solana Parabolic Trough Plant, AZ

Acknowledgments

- This work was funded by
  - DOE Office of Energy Efficiency & Renewable Energy
    - Solar Energy Technologies Office (CSP Program)
  - DOE Office of Electricity
  - DOE Office of Technology Transitions (Energy I-Corps)
  - New Mexico Small Business Assistance Program

Backup Slides

Costs and Competition



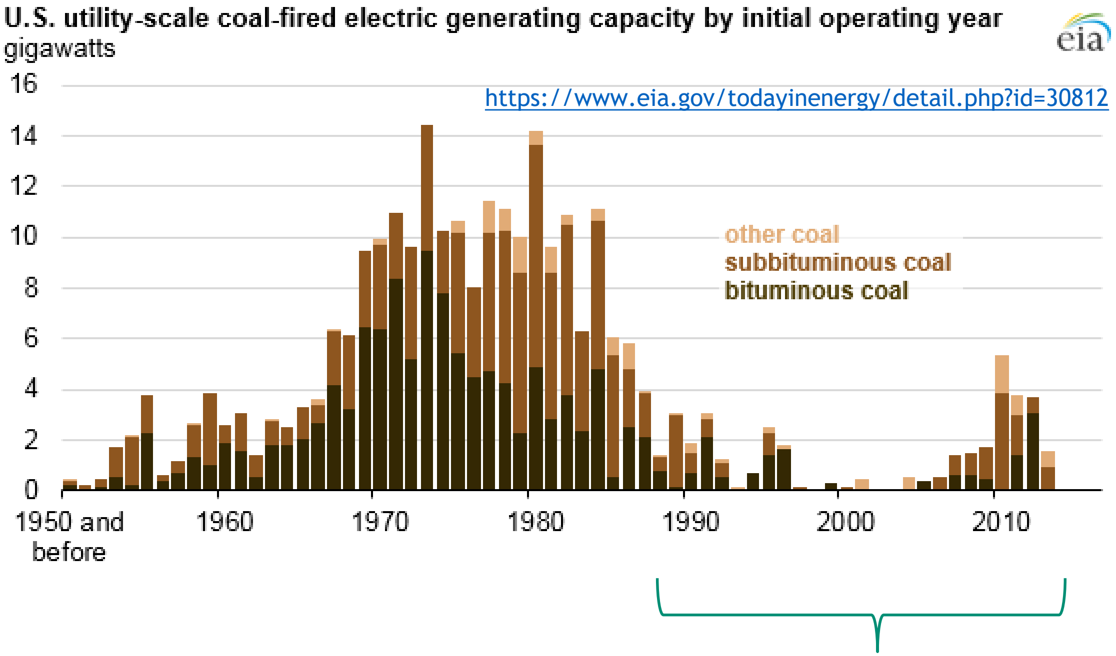
Initial Capital Cost		4 hr	168 hrs
Unit cost of basalt gravel	$/m^3	20	20
Unit cost of excavation	$/m^3	20	20
Cost of electric heater and air fan	million $	1.00	1.00
Cost of controls	million $	1.00	1.00
Cost of ducting	million $	1.00	1.00
Cost of land	million $	0.00	0.00
Site improvement cost	million $	0.10	0.10
Connection to heat recovery steam turbine, etc.	million $	2.00	2.00
Cost of engineering	million $	0.34	1.33
Cost of construction contracting	million $	0.51	1.99
Cost of owner activities	million $	0.11	0.44
Gross Receipts Tax on Direct Costs	percent	6.25	6.25
Initial Capital Cost	million $	7.10	27.54
CAPEX capital expenditure per kWh	$/kWh	31.68	2.93
Cost of Financing			
Lifetime of facility	years	30	30
Nominal interest rate, R	per year	0.06	0.06
Inflation rate, i	per year	0.02	0.02
Real Interest rate, r (discount rate)	per year	0.04	0.04
Capital Recovery Factor (CRF)	per year	0.06	0.06
Annualized Capital Cost = CRF*Initial Capital Cost	million $	0.41	1.58
Operation and Maintenance (O&M) Cost			
Number of employees	-	2	2
Loaded cost of employee per year	Million $/yr	0.10	0.10
Total cost of employees per year	Million $/yr	0.20	0.20
Cost of repairs per year	Million $/yr	1.0	1.0
Annual Operating and Maintenance Cost	Million $ per year	1.2	1.2
Cost of Purchased Electricity			
Cost of electricity for charging	$/kWh	0.03	0.03
Cost per year to charge for environmental losses	Million $	0.04	1.56
Cost per year to charge for electricity produced	Million $	3.99	1.64
Annual Cost of Purchased Electricity	Million $ / yr	4.03	3.2

THERMS cost parameters (Ho and Gerstle, 2021)

Market Incentive – Cost Avoidance for Coal Plants

- Average cost of pumped hydro, CAES, hydrogen, or long-duration battery storage = **~$0.20/kWh**[1]
- Average cost of THERMS+ = **~$0.10/kWh**[2]
- **Annual cost savings for utility:**
  - **~$10B/year in U.S.***
    - **~$100B/year globally**
  - On average, each major utility can **save ~$100M per year** using THERMS+ relative to other storage options**

In 2019, 241 coal plants with **capacity of 236 GW**



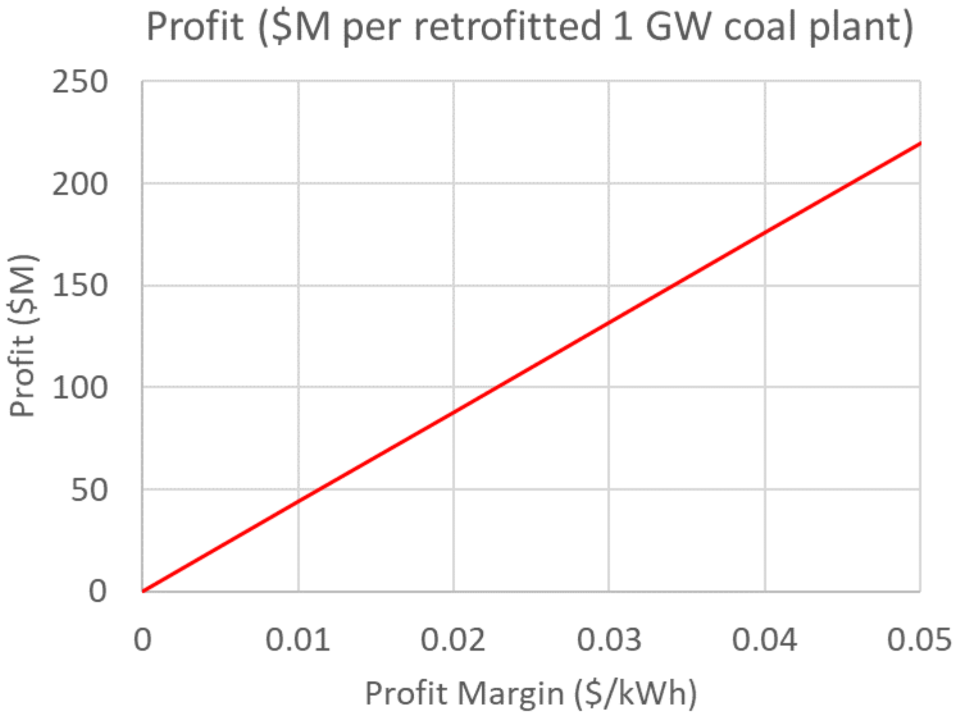
>10% of coal plants in U.S. have >20 years of useful life and will be retiring within 10 years due to emission-reduction mandates

*236 GW x 10% x 1e6 kW/GW x 8760 hours/year x 0.5 (capacity factor) x $0.10/kWh (savings) = $10B/year
**Assumes ~100 – 200 major utilities; additional savings to utility possible by using existing transmission

[1]Wang et al., Energies, 10, 991 (2017); Mayyas et al., 2020, International Journal of Hydrogen Energy, 45, 16311-16325; Wang et al., Energies, 10, 991 (2017); Ahlen et al. (2019)
[2]Ho and Gerstle, ASME ES2021, 2021

Revenue Potential

- For every \$0.01/kWh$_e$ we charge for profit after ~\$0.10/kWh$_e$ to build THERMS+, we will earn **\$44M profit per retrofitted 1 GW coal plant***
- **SOM ~\$1B in the U.S.**
  - ~20 plants x \$44M = ~\$1B



*1 GW x 1e6 kW/GW x 8760 hours/year x 0.5 (capacity factor) x \$0.01/kWh$_e$ = \$44M

Thermal Energy Storage (Sensible) - Specifications

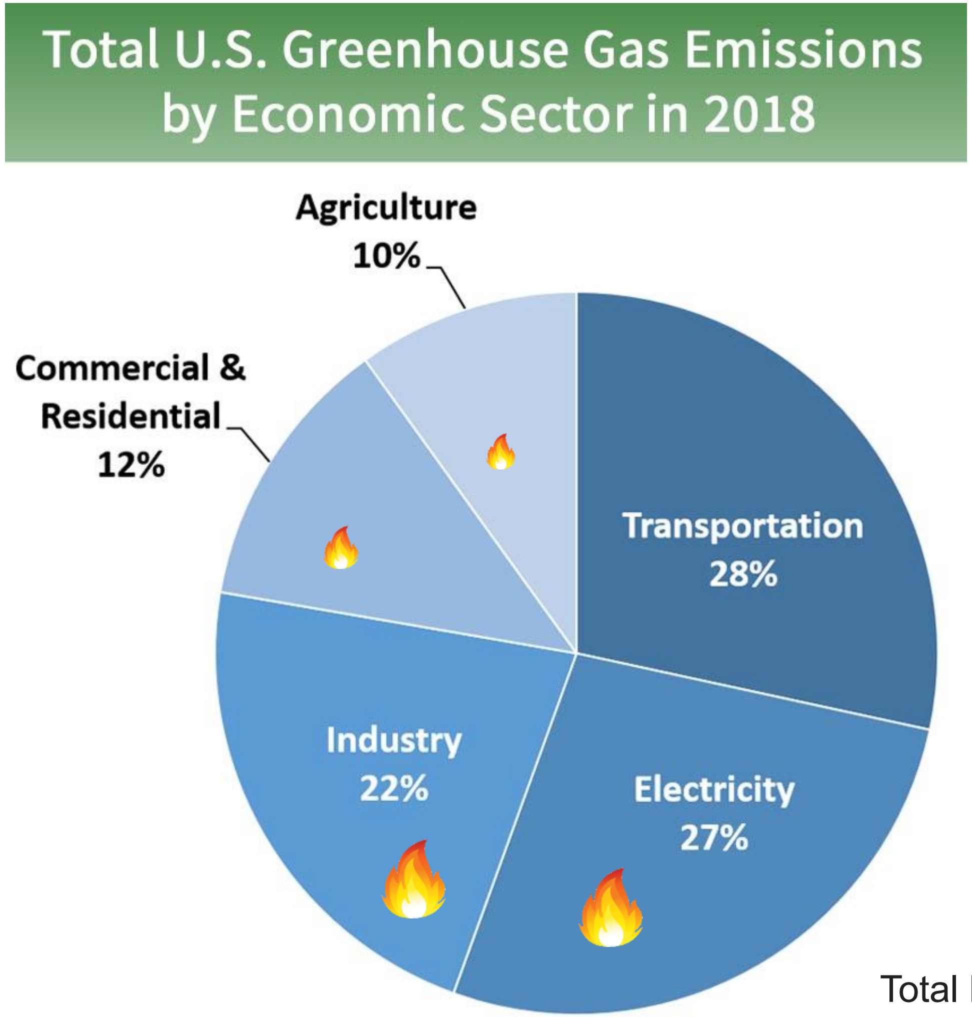
Ho, 2016, *Applied Thermal Engineering*, 109 (2016) 958-969; Siegel, 2012, *Wiley Interdisciplinary Reviews: Energy And Environment*, 1(2), 119-131.

Metric	Values	
	Solid Particles	Molten Nitrate Salt
Levelized Cost ($\$/MWh_e$)	10 - 13	11 - 17
Round-trip efficiency	>98% (thermal in/out)	>98% (thermal in/out)
Energy density (MJ/m^3)	~400 - 900	~600 - 900
System life	30 yrs (>10,000)	30 yrs (>10,000)
Toxicity/ environmental impacts	N/A	Reactive with piping materials
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	decomposes above ~600 °C

Summary of Advantages and Challenges

Storage Technology	Advantages	Challenges
Pumped Hydro	▪ Mature technology ▪ Demonstrated large capacity (~GWh); >90% of U.S. grid energy storage ▪ Good reliability	▪ Unique geologic resources and water availability ▪ Improved turbines and electrical systems ▪ Small modular pumped hydro systems
Compressed Air	▪ Demonstrated capability at large scales ▪ Moderate round-trip efficiency ▪ Good potential for long-duration storage	▪ Unique geologic resources ▪ Well integrity ▪ Repository integrity
Hydrogen	▪ Can be stored in large capacities for long periods of time ▪ Can be used for both grid and transportation ▪ Environmentally friendly	▪ Low round-trip efficiency of hydrogen production and storage ▪ High cost ▪ Leakage and safety of hydrogen gas
Thermal (Sensible)	▪ Mature technology ▪ Demonstrated large capacity with concentrating solar power (~GWh) ▪ Low cost	▪ Heat loss ▪ Large volumes required ▪ Heat exchanger performance and cost
Thermochemical	▪ Large energy density ▪ Potential for long-duration storage	▪ Low maturity ▪ High cost ▪ Material durability and kinetics

Heat Generation Contributes Significantly to CO_2 Emissions



U.S. Environmental Protection Agency (2020). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018

In 2018, heat accounted for

- 50% of global end-use energy consumption
- 40% of global CO_2 emissions

-International Energy Association
https://www.iea.org/reports/renewables-2019/heat

Total Emissions in 2018 = 6,677 Million Metric Tons of CO_2 equivalent.