Crushed-Rock Ultra-large Stored Heat (CRUSH) System with Nuclear or Concentrated Solar Power (CSP) to Provide Economic Dispatchable Electricity

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Summary

- Require dispatchable electricity (replace gas turbine)
- Most economic electricity production with base-load nuclear and CSP operating at maximum capacity
- Adding heat storage enables economic variable electricity
- Economics is central
  - Batteries >$500 MWe
  - Traditional two-tank nitrate storage $20-30 kWh of heat ($60-70/kWh(e))
  - CRUSH heat-storage capital cost: $2-4/kWh ($10/kWh(e))
- Hourly-to-weekly storage improves economics

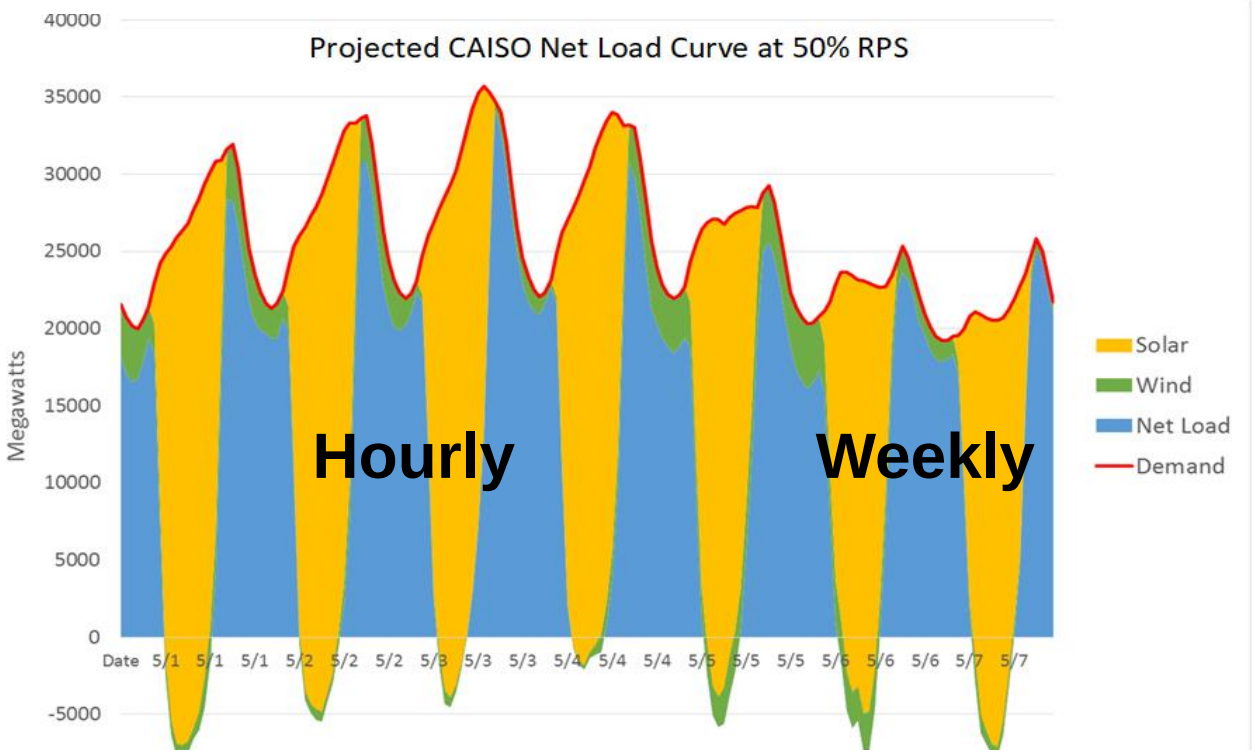
Energy Markets

Electricity Markets are Changing from Fossil Fuels where the Fuel Cost Control Electricity Costs to Nuclear, Wind and Solar where Capital Costs Determine Electricity Costs

Economics of Large-Scale Solar Are Driven by Energy Storage Costs, Not the Cost of Solar

- Electricity markets
  - Most electricity sold when no sun
  - Electricity price near zero when sun is out and solar production exceeds demand
- PV cost structure
  - Generation: $ 31.30/ MWh
  - Battery Storage: $ 121.86/ MWh
  - Battery Cap, Cost >$500/kWh(e)
- Same challenge for CSP

Projected California Production at 50% Solar/Wind vs Time over One Week



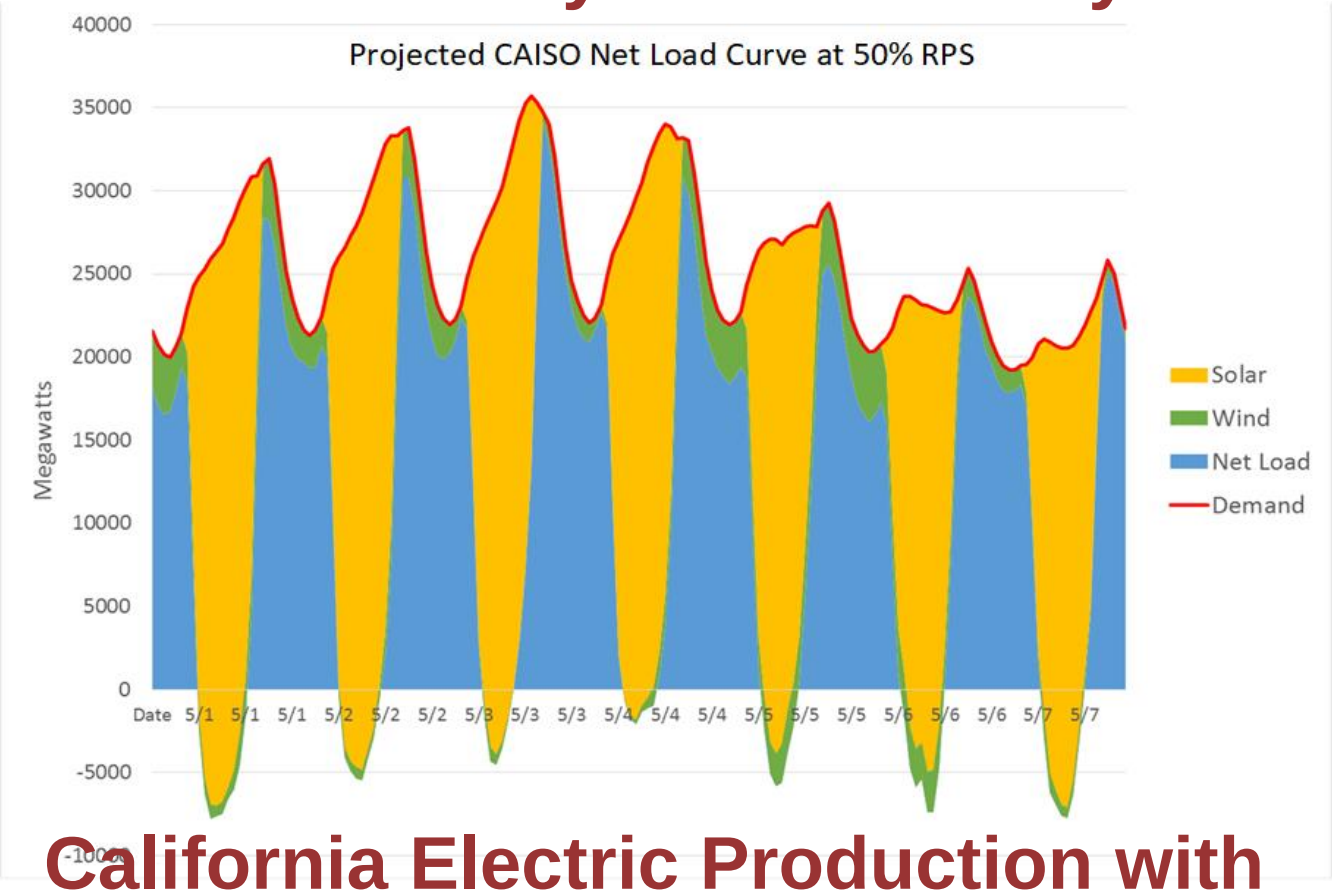
Large Incentive for Hourly to Weekend/Weekday Storage

Two Storage Strategies: Electricity and Heat

- Electricity: Lithium ion battery
  - Round-trip efficiency 81% (real systems)
  - **Capital cost today: >$500/kWh(e) with cost reductions limited by cost of raw materials**
- Heat: Efficiency >95% for nuclear and CSP
- Convert electricity to heat and back to electricity
  - Round trip efficiency 40% (Heat-to-electricity efficiency)
  - Capital cost (two-tank nitrate salt): $65-75/kWh(e)
  - **Crushed Rock Ultra-large Stored Heat (CRUCH) system capital-cost goal: $2-4/KWh heat (< $10/kWhe)**

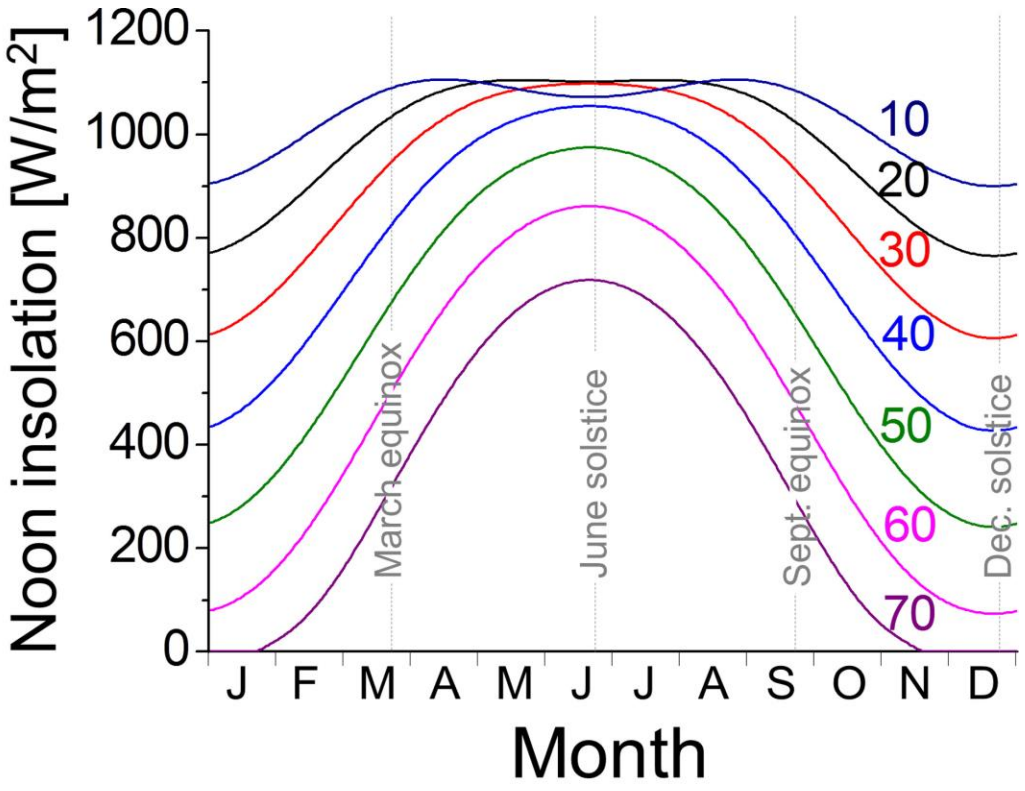
Wind and Solar Massively Increase the Storage Challenge

Daily **Weekly**



California Electric Production with 50% Wind and Solar over One Week

Seasonal (Peak Solar in June)

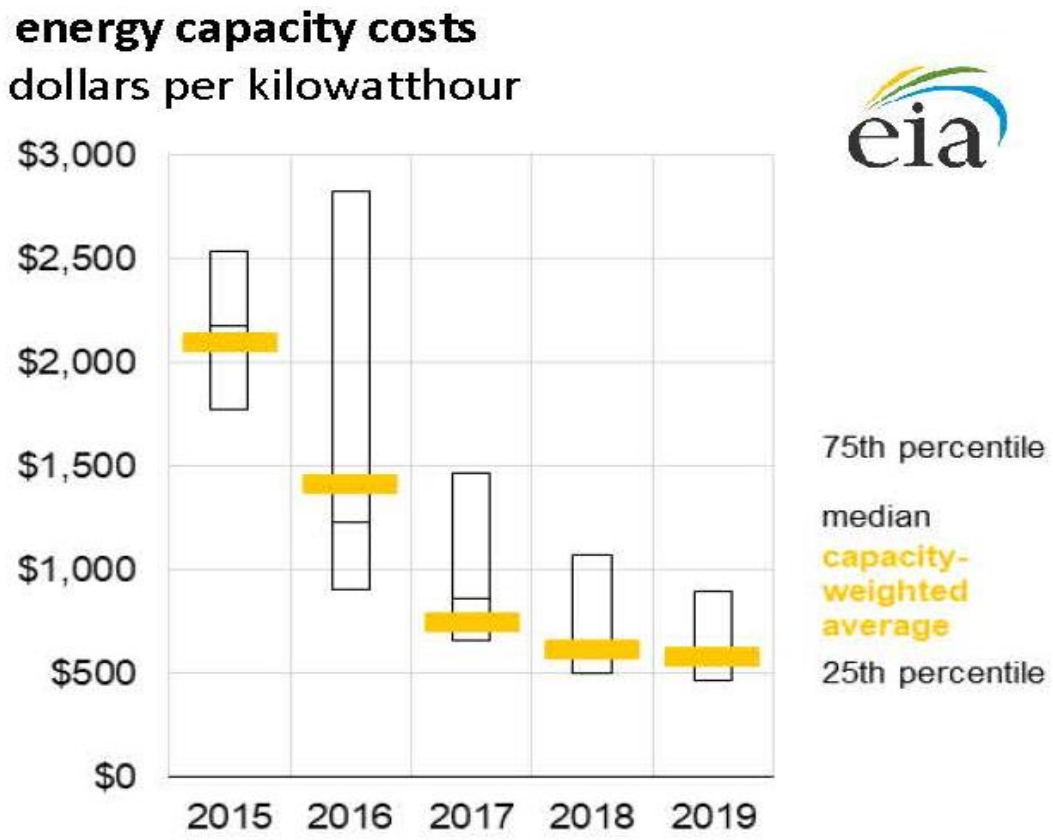


Solar Flux Over a Year at Noon Versus Latitude

Published in: F. M. Mulder; *Journal of Renewable and Sustainable Energy* **6,** 033105 (2014),DOI: 10.1063/1.4874845; Copyright © 2014 Author(s)

Batteries Are Not a Solution to a Million-Gigawatt-Hour Energy Storage Challenge

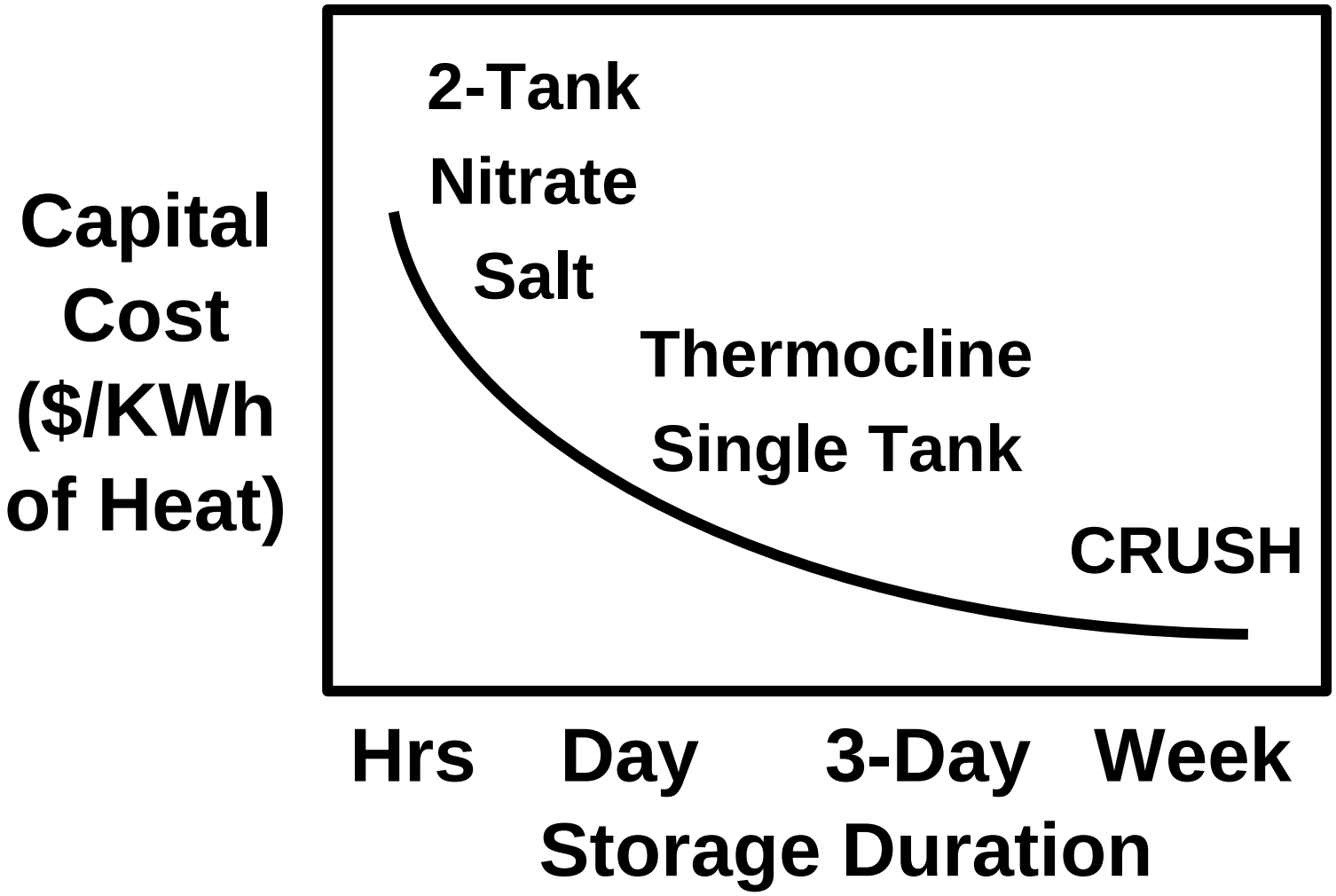
- Battery capital cost leveling off at $500/kWh(e)
- $500 trillion for a million-gigawatt hours of storage
- U.S. Gross National Product is $22 trillion
- Battery cost more than 20 times U.S. GNP



C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal,* 34 (10) 107042, December 2021. https://doi.org/10.1016/j.tej.2021.107042

U.S. Energy Information Agency, August 2021. *Battery Storage in the United States: an Update on Market Trends*

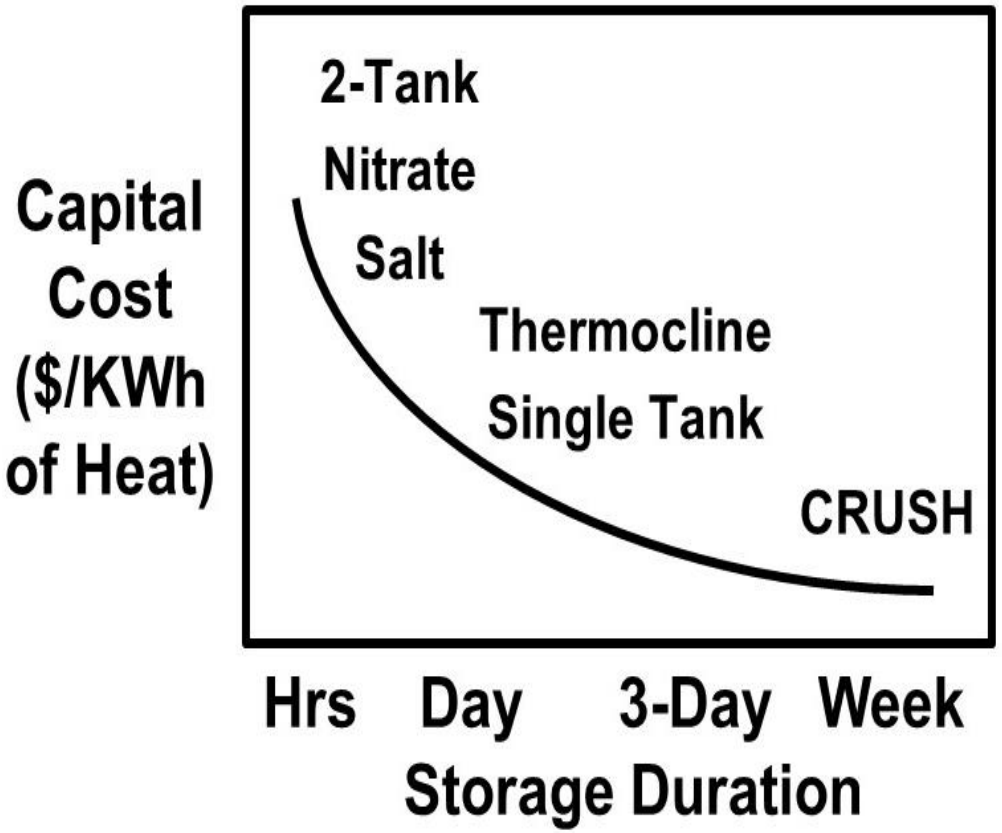
Allowable Cost Versus Storage Duration



Duration	Event
Hours-Day Sunlight (200+ cycles per year)	Solar PV Electric Demand
3-Day Weather (100 cycles per year)	Wind Heating Air Conditioning
Week (50 cycles per year)	Weekday/Weekend Demand

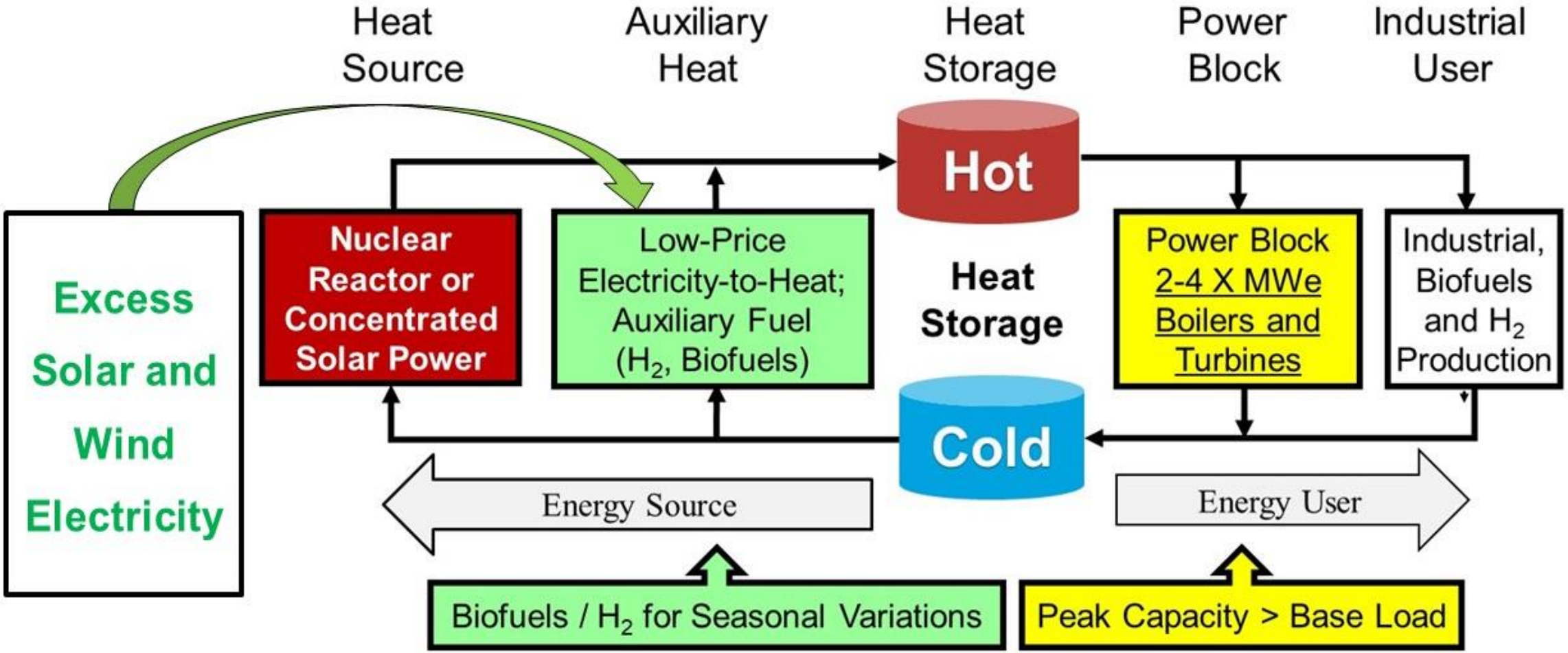
Incremental Capital-Cost Goal: $2-4/KWh of Heat

- Some capital costs associated with rates of heat input and output (pumps)
- Storage capital costs
  - Can pay more for parts of system used for daily storage (300 time per year)
  - Require low incremental capital costs if weekly use (50 times per year)—weekend/weekday



System Design

System Design for Nuclear or CSP with Heat Storage



Thermal Energy Storage at Concentrated Solar Power Plants

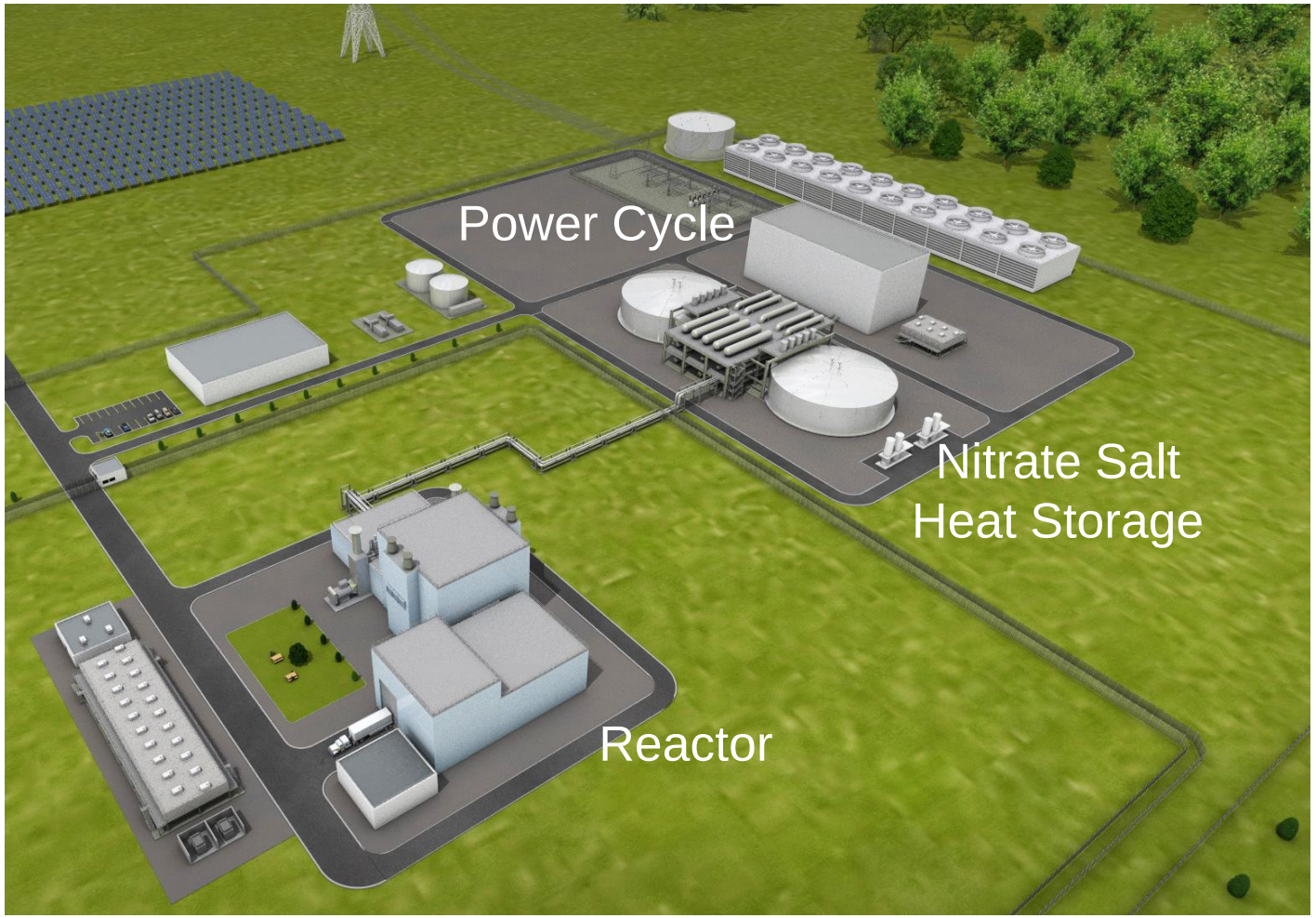
Molten salt thermal energy storage

Solana Generating Station
(2013, U.S., ~4200 MWh(t))

Solar System Heats Cold Nitrate Salt and Puts in Hot Storage Tank

Advance Nuclear Systems Planning to Use Same Salt Heat-Storage System—Natrium Example

- GE/Terrapower
- First plant to be built in Wyoming
- Nitrate salt storage (same as CSP)
- Baseload: 345 MWe, variable power 100 to 500 MWe



Crushed Rock Ultra-Large Stored Heat (CRUSH) System with Oil or Nitrate Salt Heat Transfer

Traditional Nitrate-Salt-Storage Cost Structure

- EPRI study: 3500 MWh(t) of heat storage
- Cost breakdown
  - Tank: 50%
  - Nitrate Salt: 34.4%
  - Other: 15.6%
- Oil storage costs are higher

EPRI, Solar Thermocline Storage Systems Preliminary Design Study, 1019581,June 2010

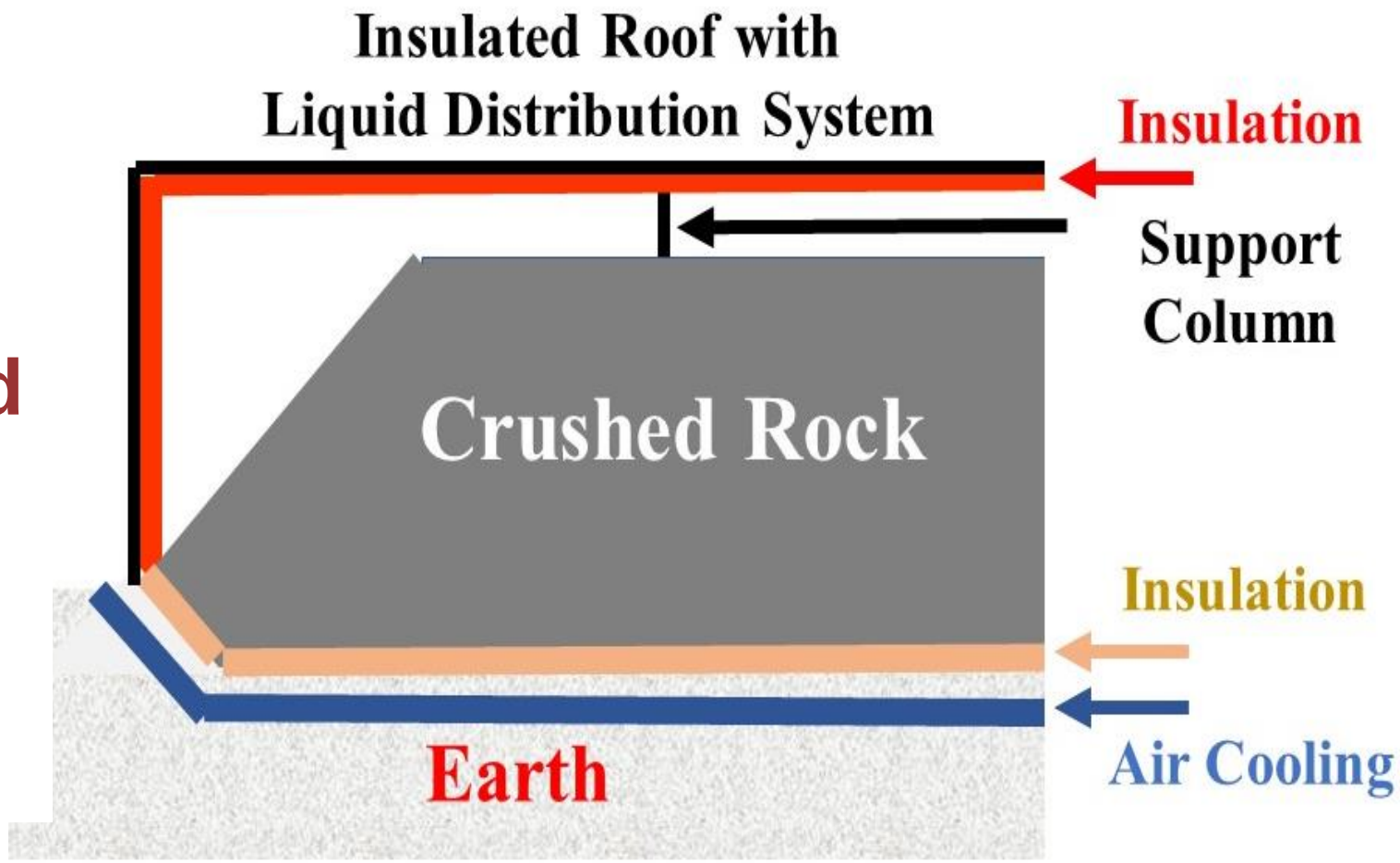
For low costs

Can't afford expensive high-temperature tank

Can't use nitrate salt for heat storage

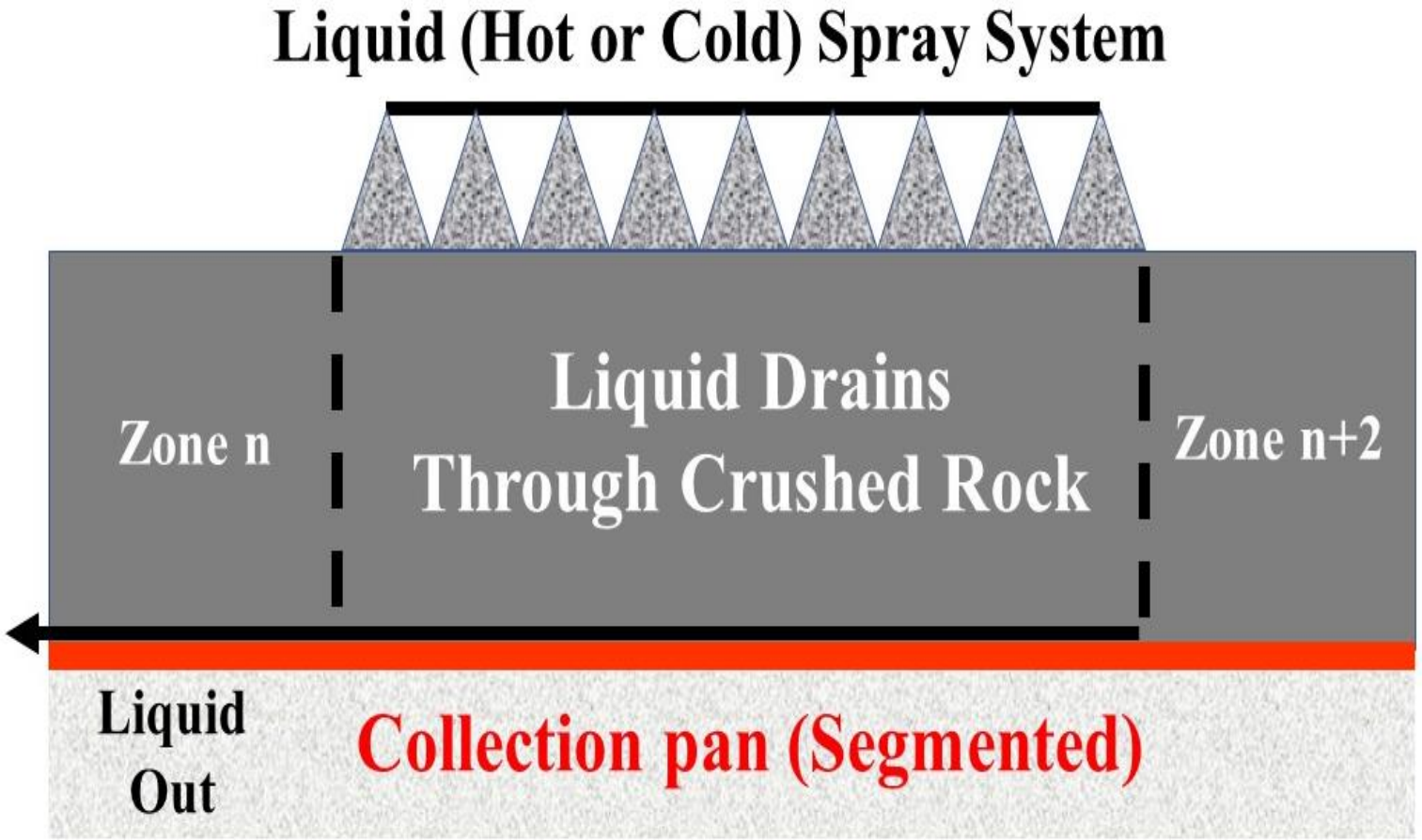
CRUSH System Stores Heat as Crushed Rock in Insulated Structure Similar to Aircraft Hangar

- Crushed Rock Lowest-Cost Heat Storage Material
- Low-Cost Insulated Building with 20+ Meter High Crushed Rock



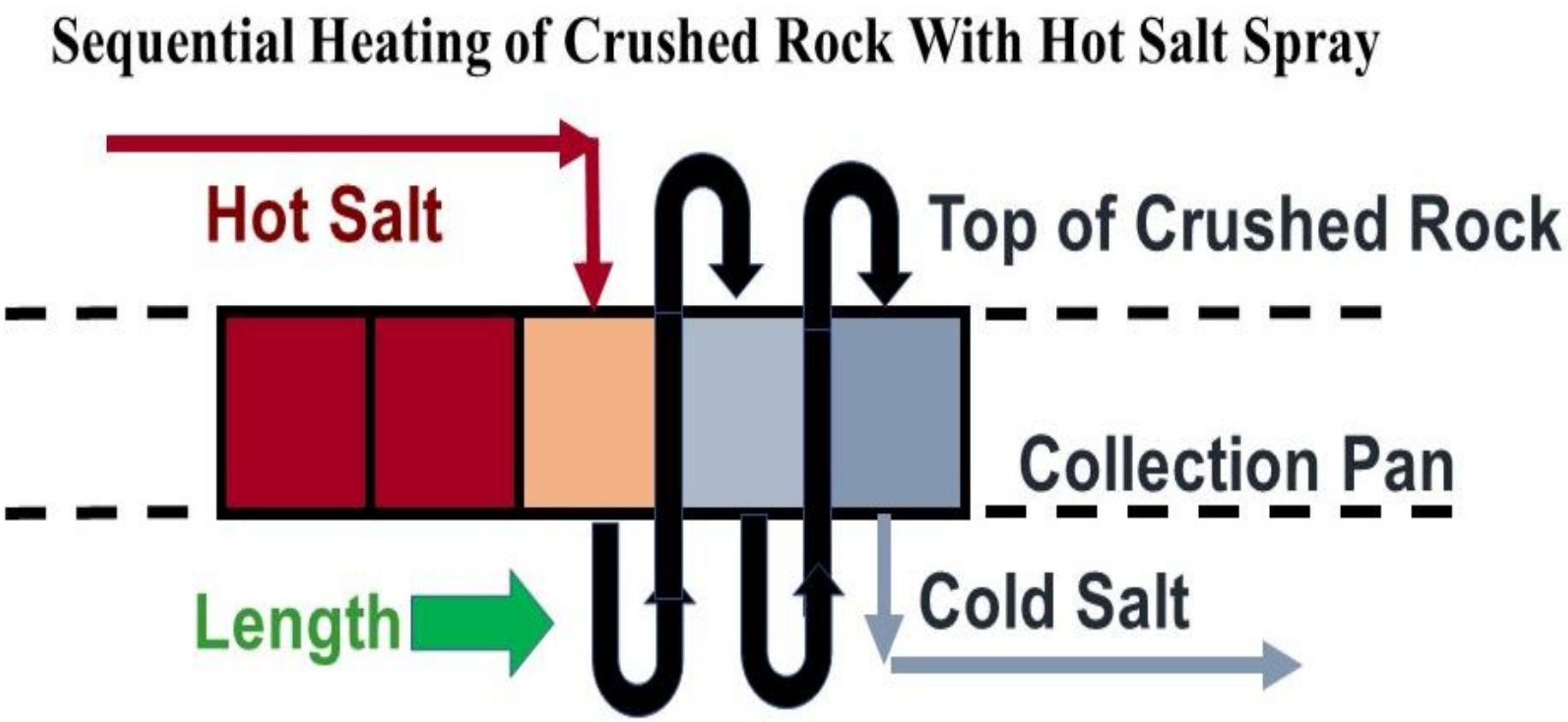
Transfer Heat to and from Crushed-Rock Heat Storage With Liquid Oil or Nitrate Salt

- Spray hot or cold fluid over rock with gravity flow to salt or oil pan at bottom
- **Minimize heat transfer fluid inventory and cost, <u>liquid moves heat, not heat storage</u>**

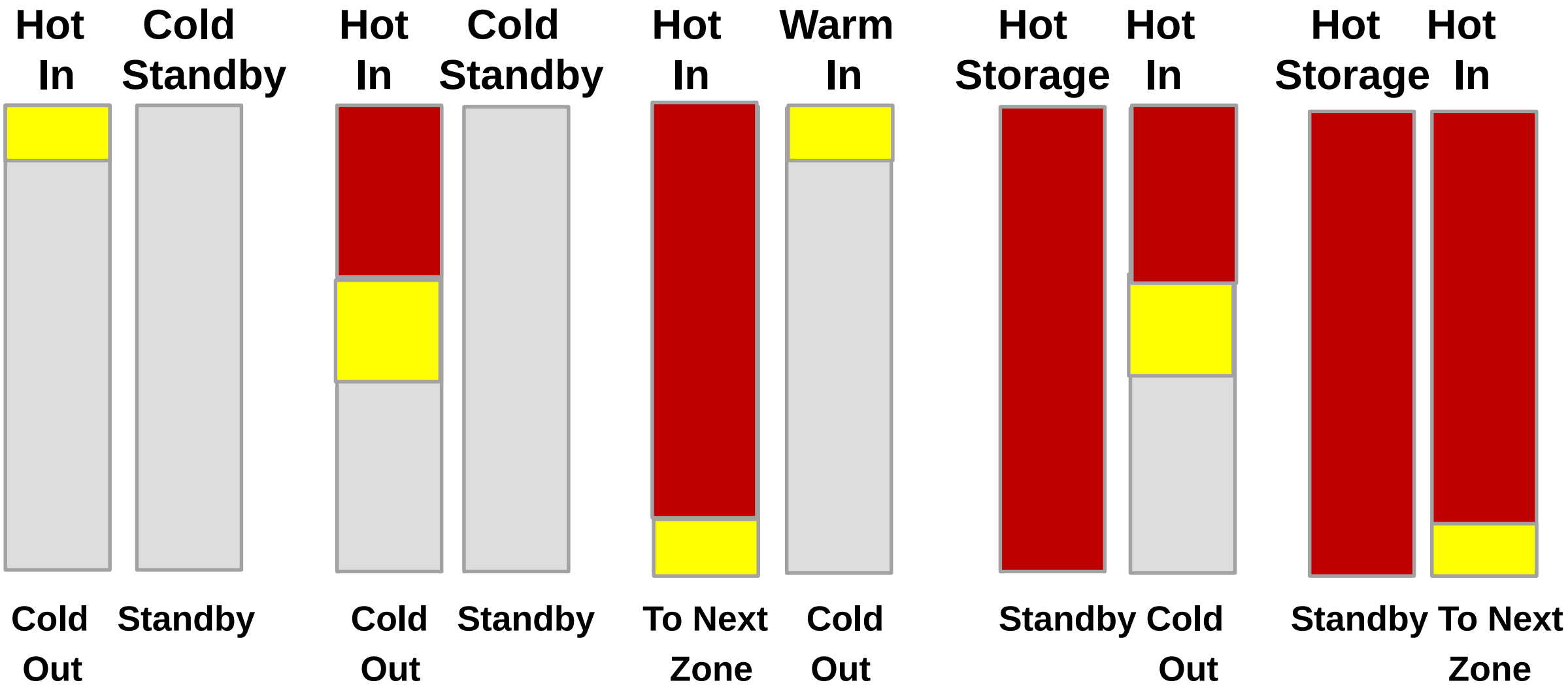


Sequential Heating or Cooling of Crushed Rock Section by Section with Hot Fluid Flowing By Gravity

Side View



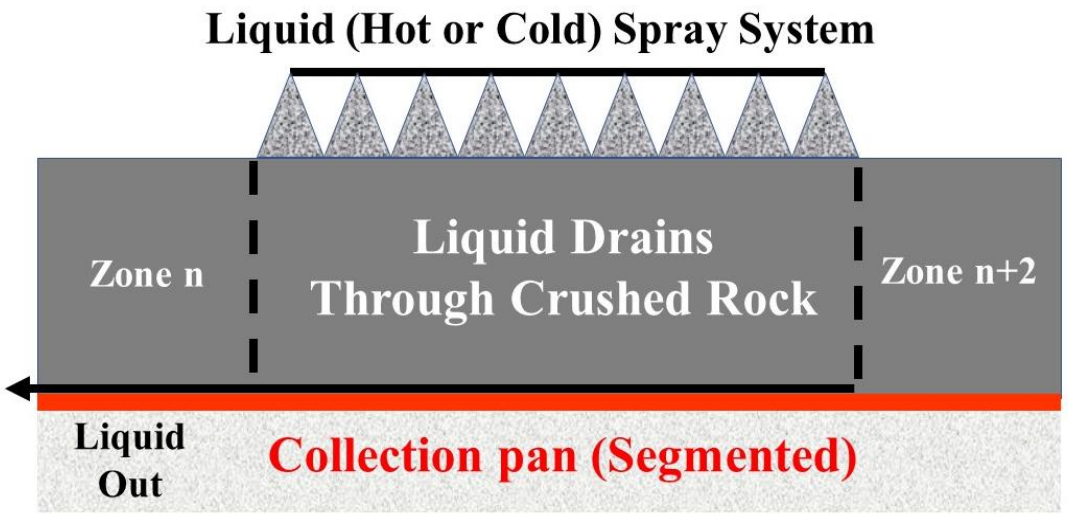
Sequential Heating of Adjacent Zones with Hot Fluid

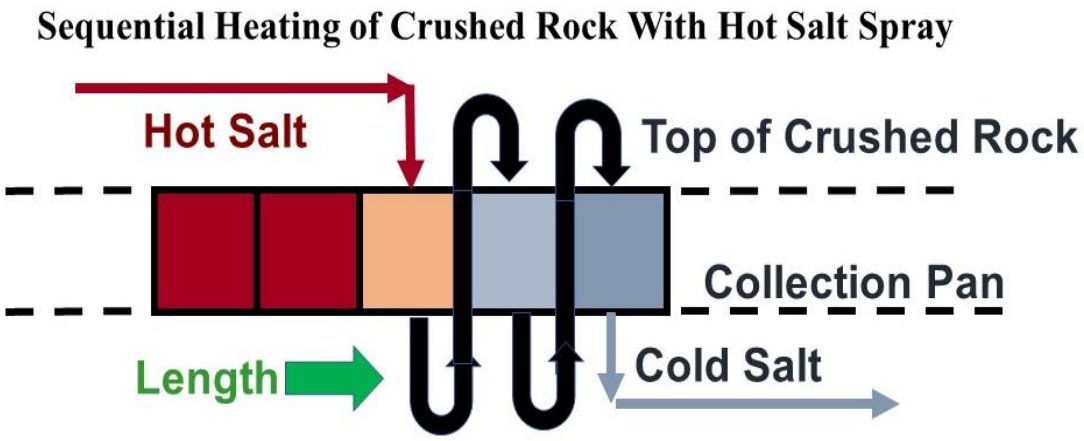


Hot Rock Heating Zone Cold Rock

Sequential Heating Addresses Other Potential Challenges of Large Systems

- If non-uniform heating, can do second heating of zone x-hours later after temperatures equilibrate
- Partly-cooled fluid dumped on cold rock being initially heated
- Viable because of very low incremental heat storage costs—can have a gigawatt-hour of heat storage used in operations.



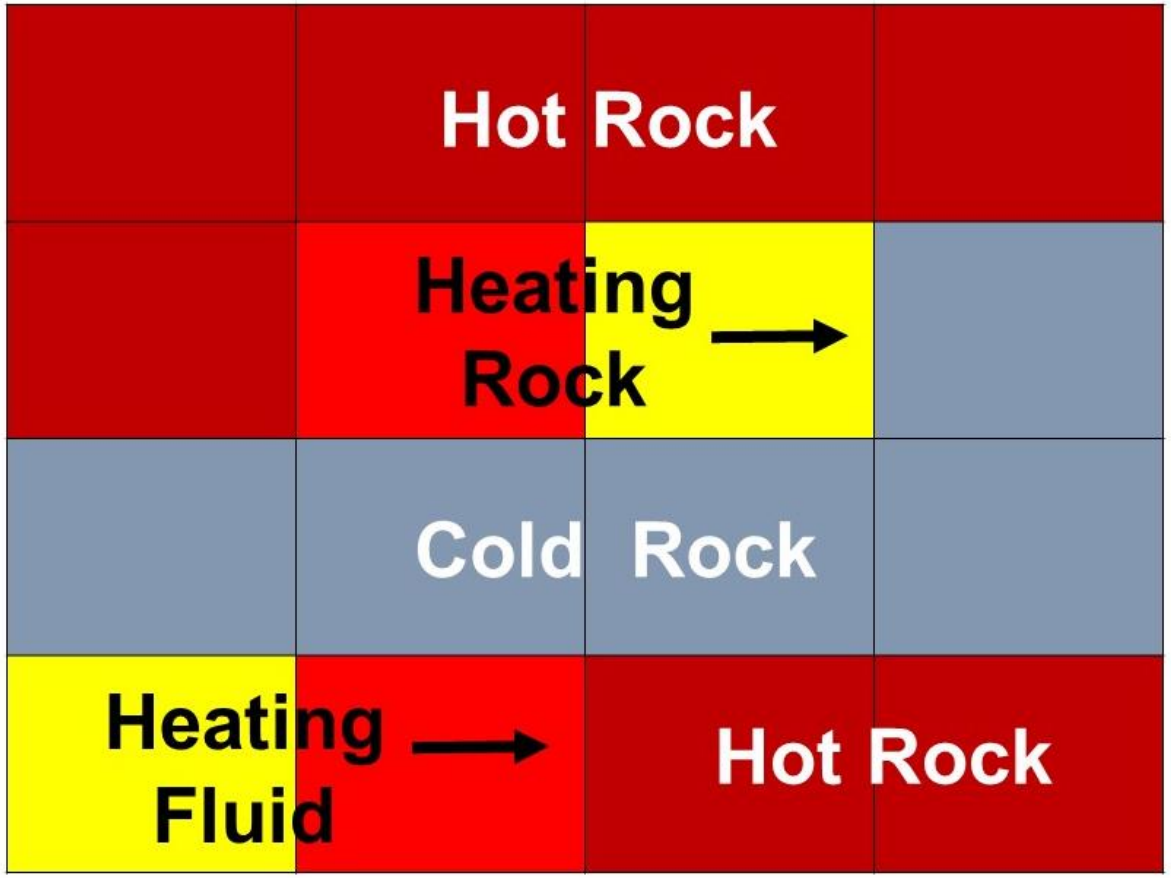


CRUSH Heat-Transfer System is Similar to Mass Transfer in Heap Pile Leaching of Copper Ores

- 20% of global copper recovered by heap pile leaching
- Spray liquid on crushed ore, flow through pile, leach copper and collect liquid
- Many features similar to heat transfer in CRUSH

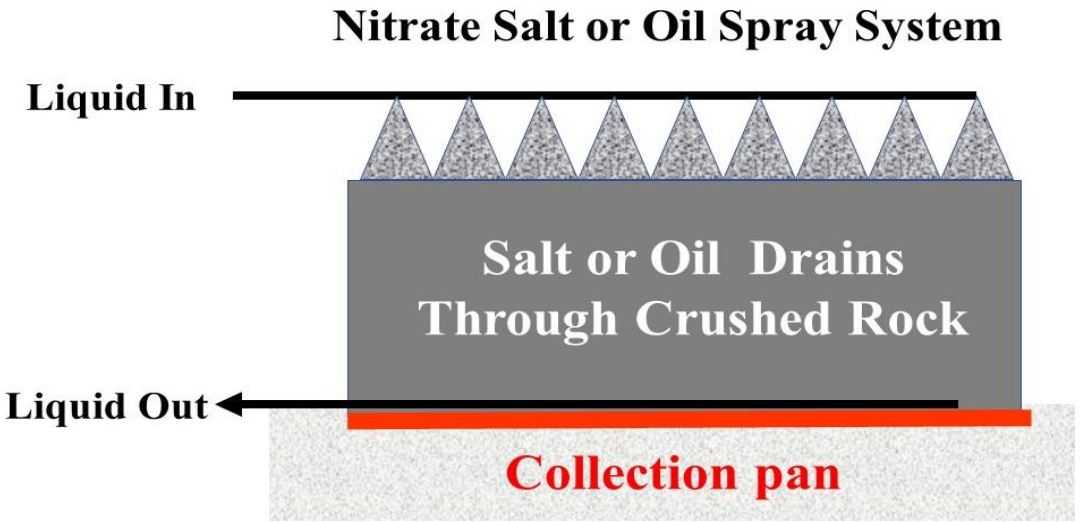
Rock Pile Size Adjusted for 1 to 100 GWh with Multiple Zones (GWh ~ 20 m by 25 m by 25)

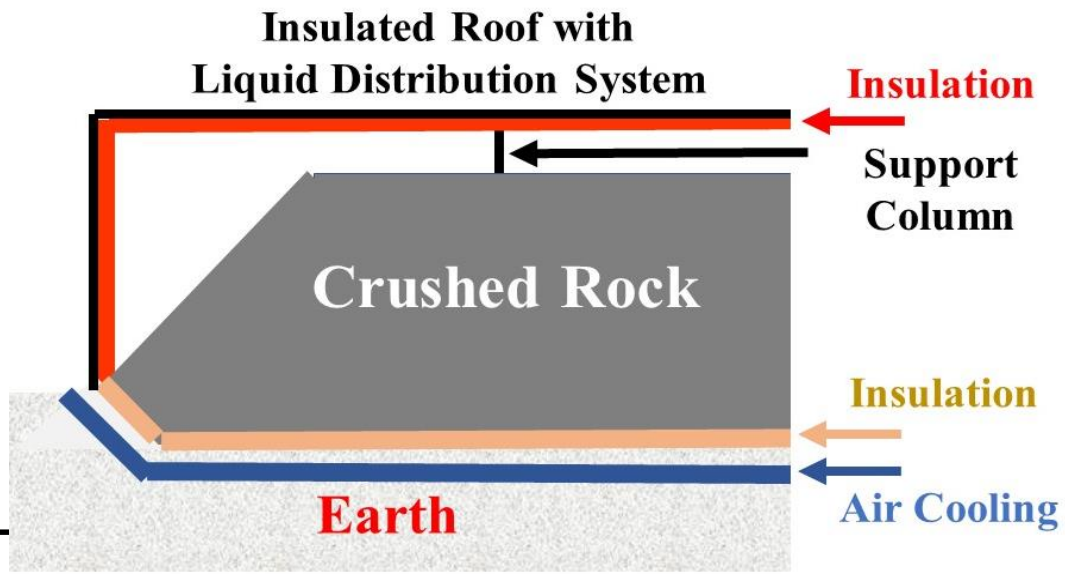
- 25 m by 25 m heating and cooling zones
- Crushed rock without flowing salt acts as a partial insulator
  - Low-conductivity crushed rock—touch at points
  - Gas between rocks acts as insulator



Gravity Flow of Liquid Reduces Building Costs

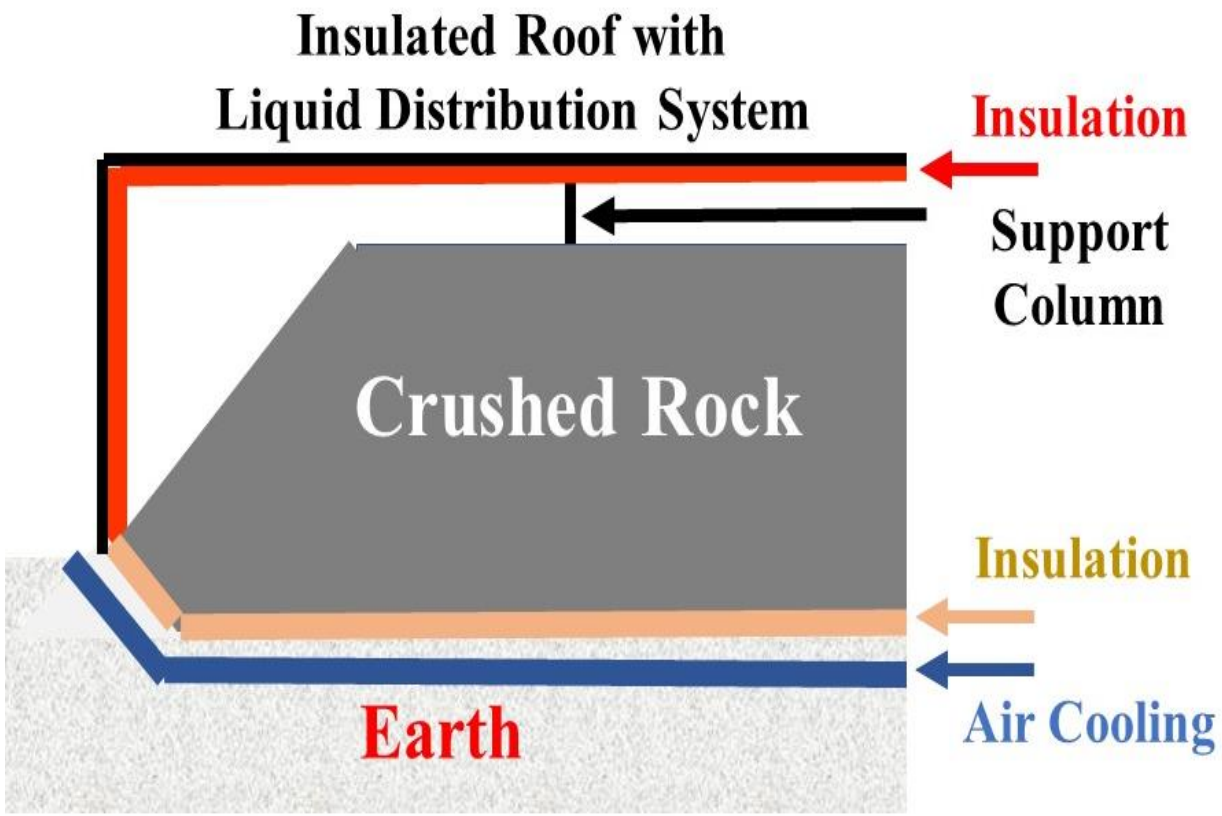
- Side walls do not have to withstand liquid hydraulic pressures, enables tall storage systems
- No rock pressure against side walls with free expansion of liquid
- **Lightweight aircraft-hanger-type structure with internal insulation**





Requirements for Low Cost Buildings

- Building only provides gas-tight insulted structure, no liquid or rock containment
- Crushed rock pile
  - Flat top
  - Sloped walls of crushed rock
- Free expansion of rock with temperature



Light-Weight Building Similar to Insulated Aircraft Hanger

Massive Aircraft Hangar Building Experience

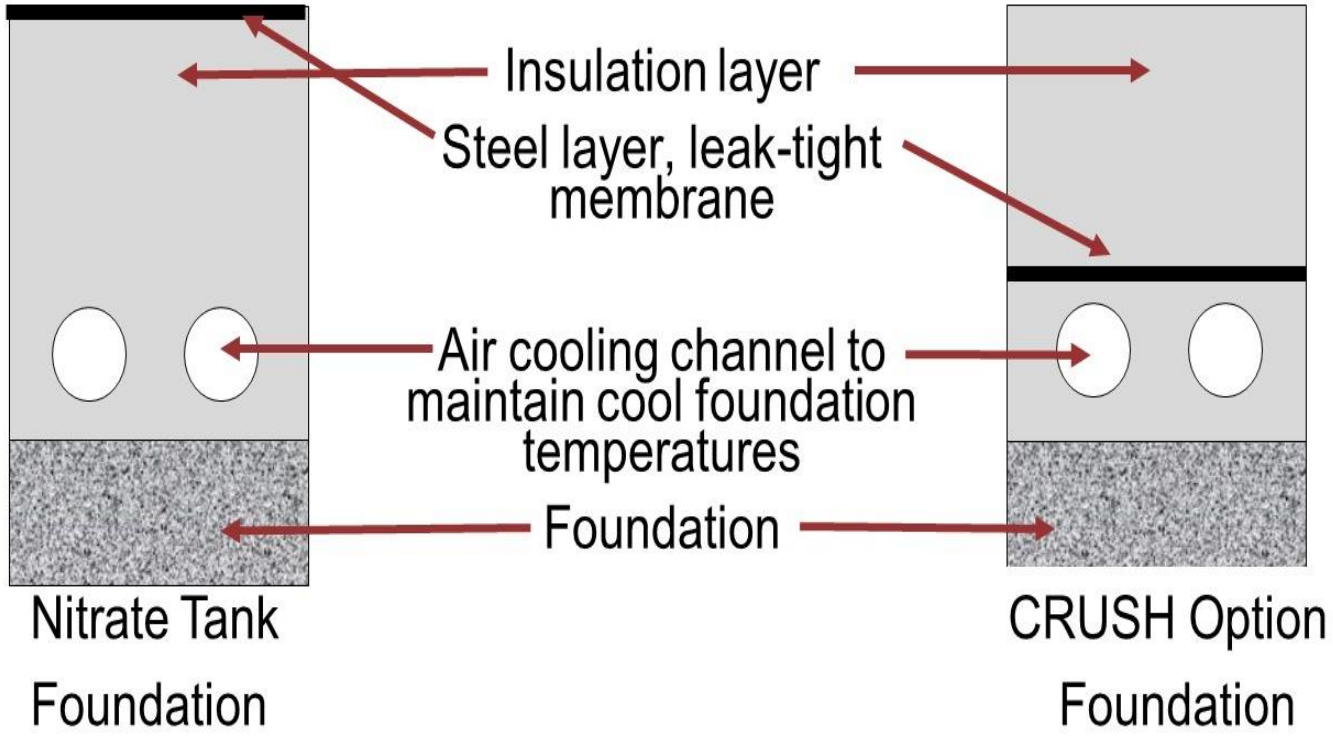
Tillamook Air Museum, Oregon (Width: 269 feet., length 1072 feet, height 192 feet)

Hanger 375, San Antonio, Texas (610 x 90 x 27.5m; 2,000 x 300 x 90 ft; 600,000 square feet

http://www.lib.utexas.edu/taro/utsa/00297/utsa-00297.html

Foundation Designed for Temperature Transients

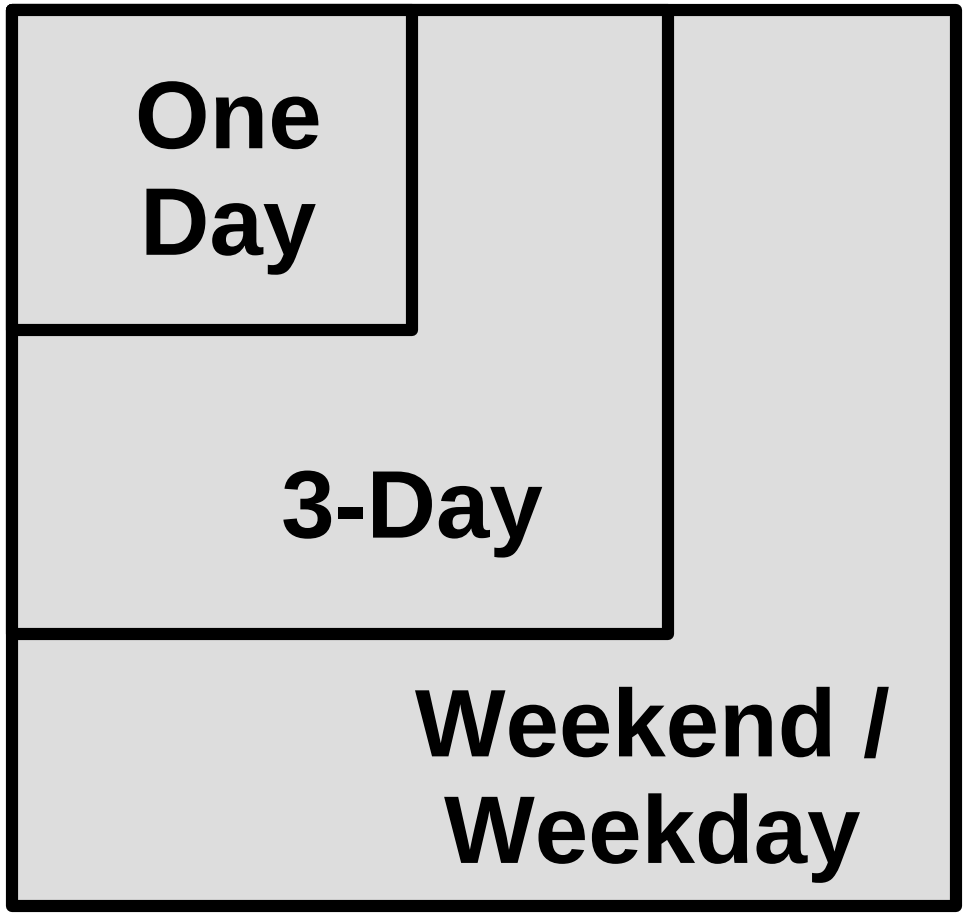
- Two-tank nitrate salt tanks see few temperature transients
- CRUSH foundation sees many temperature transients
- Road-bed insulation layer (firebrick or sand/other mixture) addresses multiple temperature transients
- Insulation is the collection pan for the salt or heat-transfer oil



Only Insulation Sees Temperature Transients (Road-Bed Construction)

Extremely Low Incremental Capital Cost As Boost Capacity

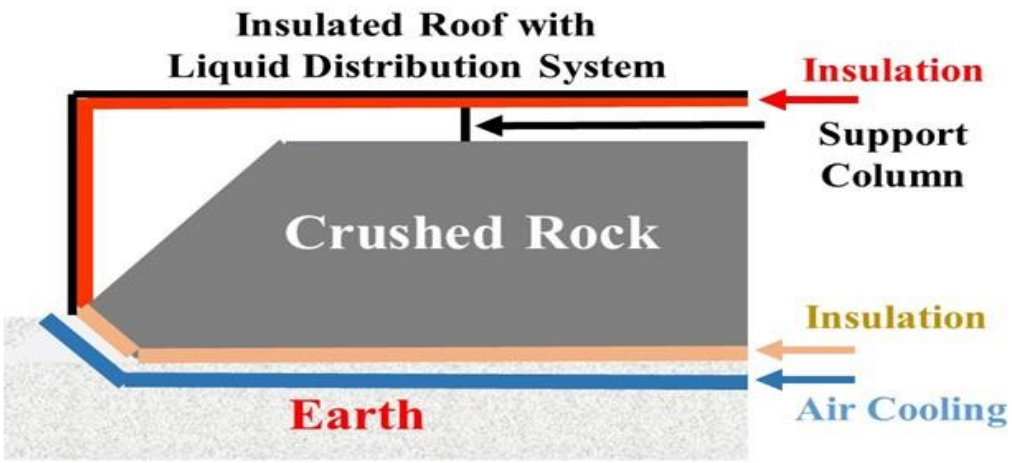
- Building cost structure favors larger capacity
  - Heat capacity (volume) goes up as cube
  - Cost goes up as surface area—square (Incremental foundation and roof for building)
- Low-cost crushed rock
- Added fluid limited to residual on crushed rock

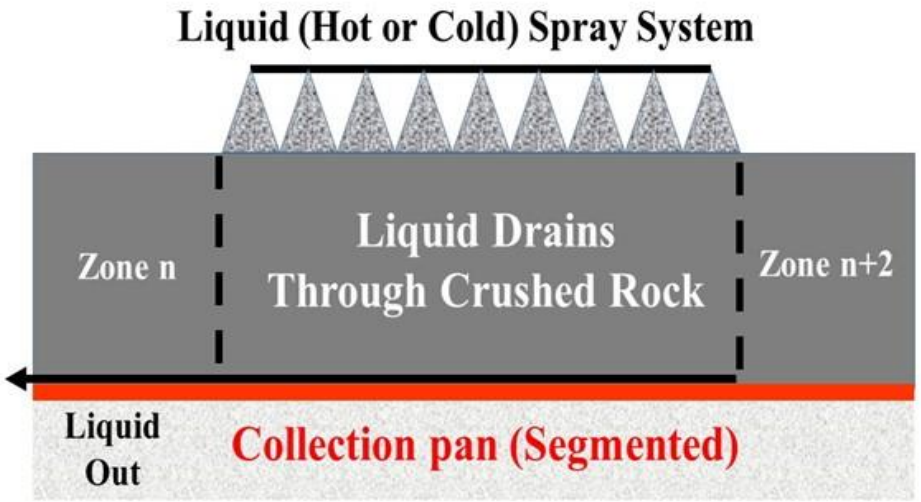


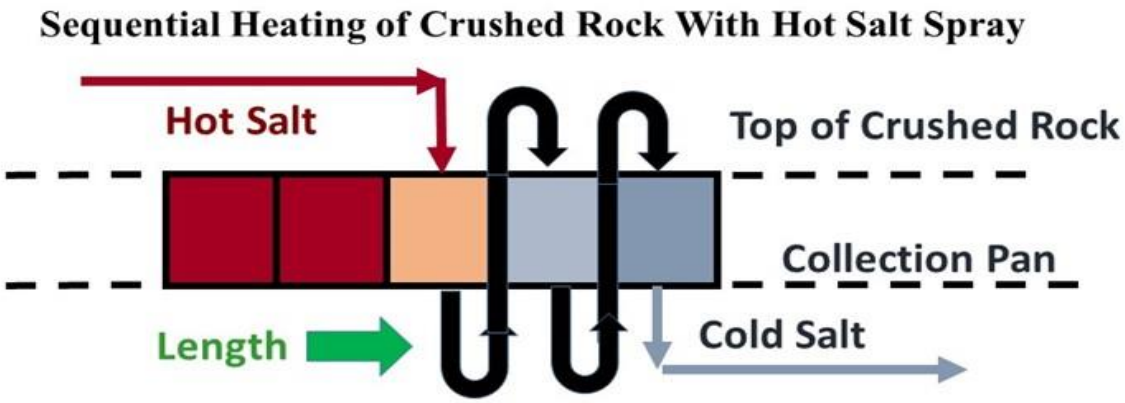
Conclusions

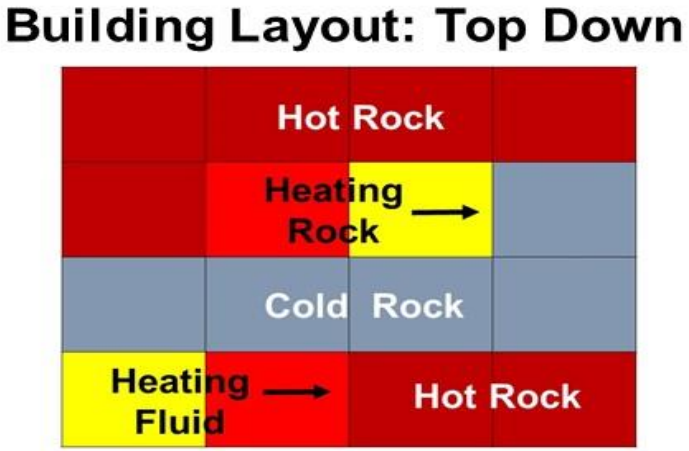
- **Low-carbon world requires dispatchable electricity—replacement for gas turbine**
- Can use base-load nuclear and CSP with heat storage to minimize electricity generation costs
- CRUSH incremental capital-cost goal: $2-4/kWh of heat
  - Crushed rock for low-cost heat storage
  - Nitrate salt or heat-transfer oil to move heat to/from crushed rock
  - Low-cost aircraft-hanger type building (no expensive tanks)
  - Foundation design for multiple temperature transients
- Early stages of development

Questions


Insulated Roof with
Liquid Distribution System
Insulation
Support
Column
Crushed Rock
Insulation
Earth
Air Cooling


Liquid (Hot or Cold) Spray System
Zone n
Liquid Drains
Through Crushed Rock
Zone n+2
Liquid
Out
Collection pan (Segmented)


Sequential Heating of Crushed Rock With Hot Salt Spray
Hot Salt
Top of Crushed Rock
Collection Pan
Length
Cold Salt


Building Layout: Top Down
Hot Rock
Heating
Rock
Cold Rock
Heating
Fluid
Hot Rock

Acknowledgements

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Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh heat storage systems. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

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1. C. W. Forsberg, “Separating Nuclear Reactors from the Power Block with Heat Storage to Improve Economics with Dispatchable Heat and Electricity”, *Nuclear Technology*, August 2021. https://doi.org/10.1080/00295450.2021.1947121 (Accessed 21 February 2022)
2. C. Forsberg, “Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge“, *The Electricity Journal,* 34 (10) 107042, December 2021. https://doi.org/10.1016/j.tej.2021.107042 (Accessed 21 February 2022)
3. C. W. Forsberg, “100-Gigawatt-Hour Crushed Rock Heat Storage for Variable Electricity and heat with base-load reactor operations,” ICONE28-64632 , *Proceedings of the ASME 2021 International Conference on Nuclear Engineering*, ICONE 28, (August 4-6, 2021).
4. A. S. Aljefri, *Technical and Economic Feasibility of Crushed Rock with Synthetic Oil Heat Storage Coupled to Light Water Reactors in the United Arab Emirates*, Master Thesis, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, (2021). https://dspace.mit.edu/bitstream/handle/1721.1/139910/Aljefri-aljefri-sm-nse-2021-thesis.pdf?sequence=1&isAllowed=y [Accessed 21 February 2022]
5. C. W. Forsberg, “1000-MW CSP with 100-Gigawatt-Hour Crushed-Rock Heat Storage to Replace Dispatchable Fossil-Fuel Electricity”, SolarPaces2021; Paper 7281, September 27-October 1, 2021

Alternative CRUSH / CSP System Designs

The Low Incremental Capital Cost of CRUSH May Change Large-Scale CSP/PV System Design

Conventional Heat Storage Economics of Scale End at a few Gigawatt Hours

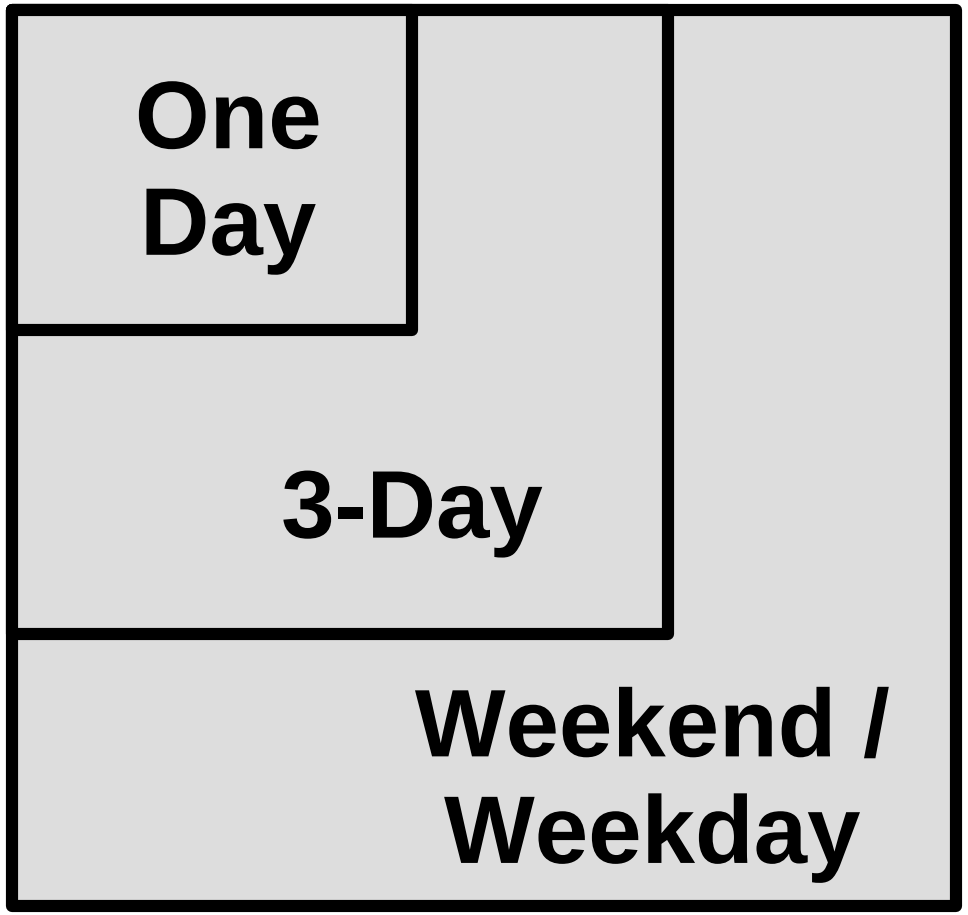
- Cost of tanks
- Cost of nitrate salt or heat transfer oil

Molten salt thermal energy storage

Solana Generating Station (2013, U.S., ~4200 MWh(t))

Crush System Costs Decrease Rapidly with Size

- Crushed rock cheap
- Incrementally larger building costs are low—doubling building size does not double cost
- **Costs decrease as go from a few to 100 GWh**

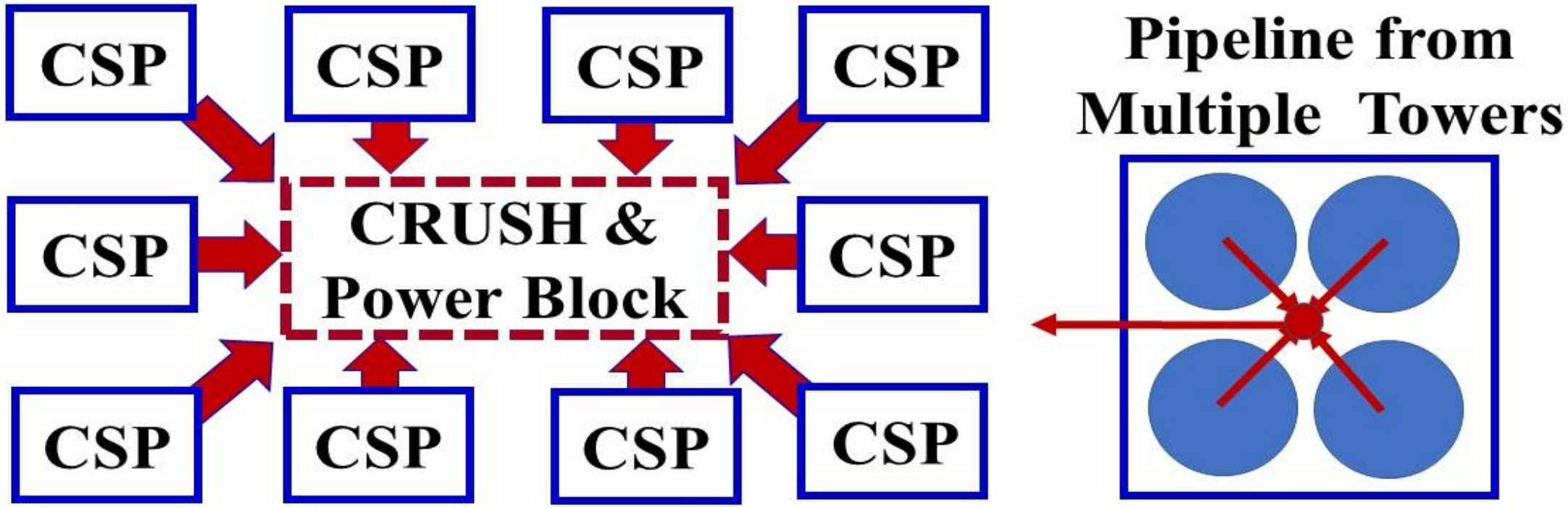


Economics of Storage / Power Block Drives to Large Sizes to Minimize Costs and Maximize Revenue

- CRUSH system for 100 GWh of heat storage
- Enables daily to weekday / weekend heat storage to maximize revenue
- Similar in capabilities to TVA Raccoon Mountain pumped storage facility

TVA Raccoon Mountain Pumped-Storage Plant: 1,652 MW maximum output for 22 hours

Large-Scale Storage Supports Multiple CSP Systems Moving Heat to Central Storage via Pipeline



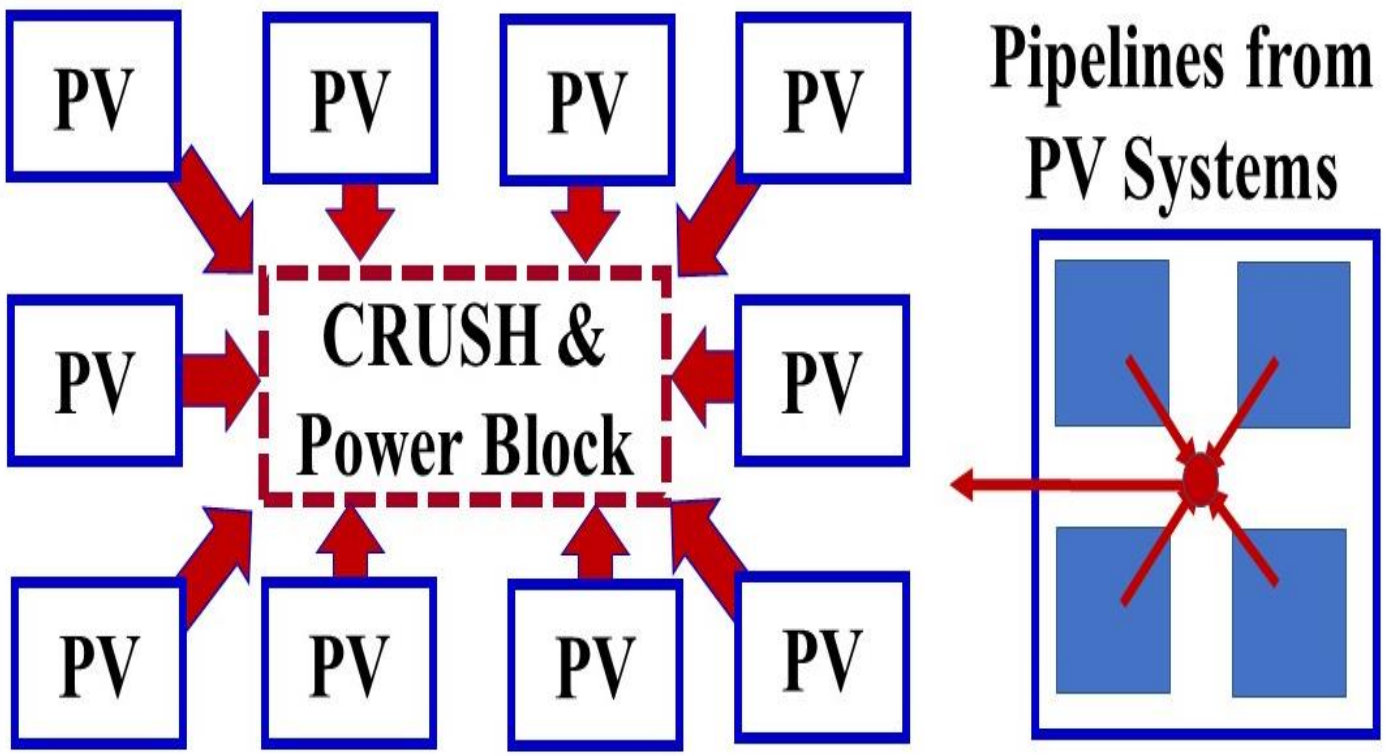
Many CSP Plants Pump Hot Fluids to CRUSH System and Power Block;

Low-Cost CRUSH and Power Block Require Gigawatts of Heat Input

CRUSH System Coupled to Photovoltaic System

Use Where Limited Direct Sunlight

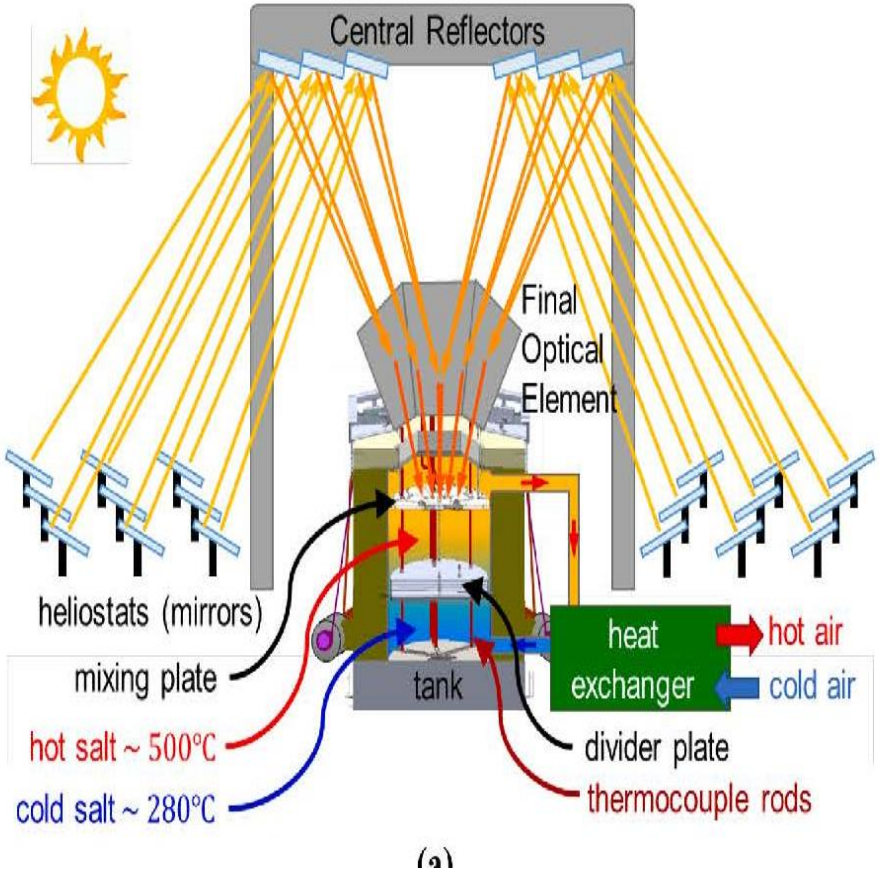
- Collector fields greater than 100 km^2
- PV direct current heats salt with pipeline heat transfer to central heat storage several kilometers away
- Avoid DC-AC-transformer-line-transformer-resistance heater losses and costs



Alternative Option of Electricity Transfer to CRUSH and Power Block

CRUSH System Coupling to Concentrated Solar Power on Demand (CSPond) System-I

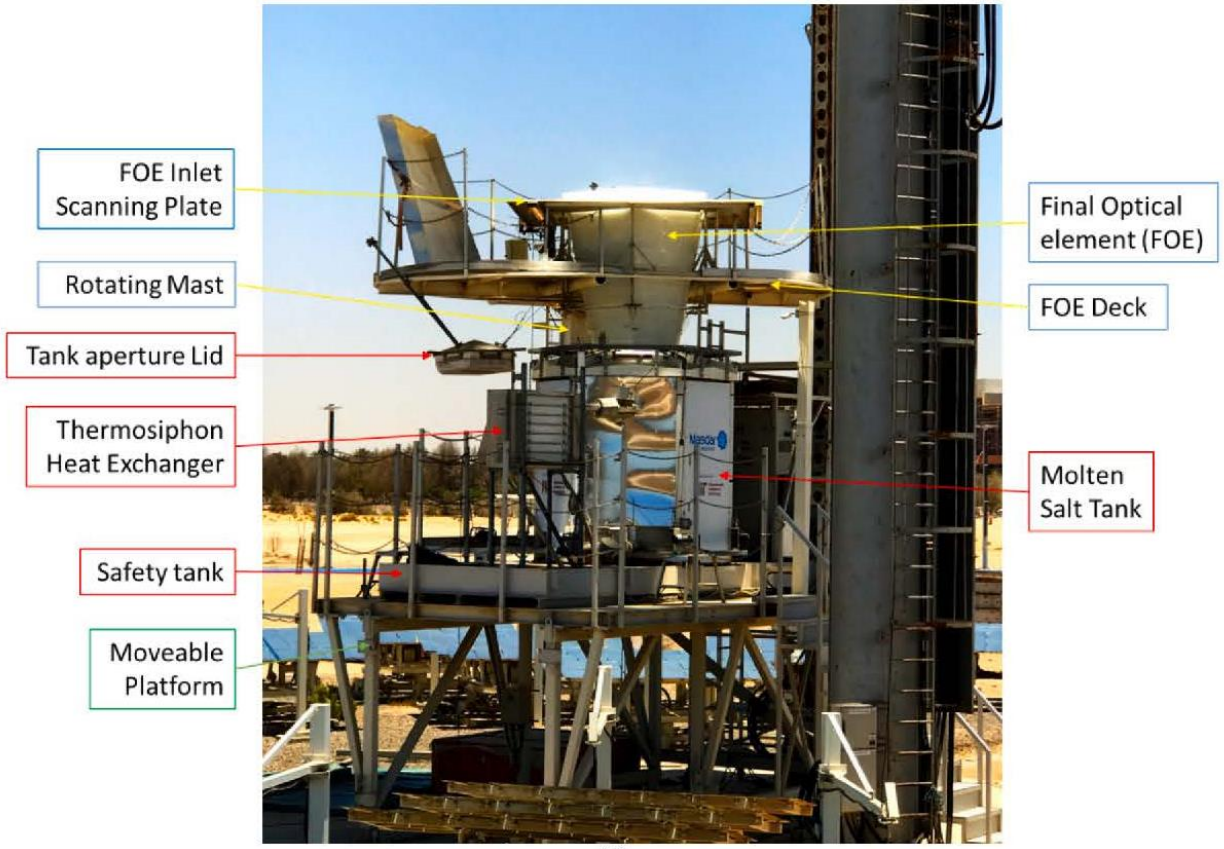
- Advanced CSP where sunlight reflected off secondary mirrors into pool of nitrate salt open to atmosphere on the ground
- Volumetric collector that avoids heat flux limits of conventional collectors
- CRUSH and CSPond nitrate salts have high impurity levels



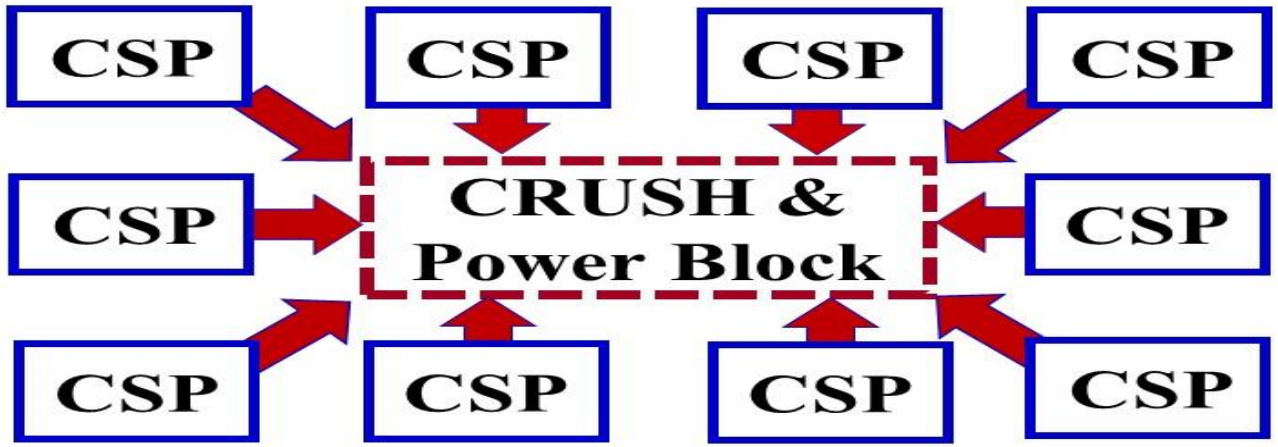
N. Calvet et. al., "Dispatchable Solar Power Using Molten Salt Directly Irradiated from Above", Solar Energy 220 (2921) 217-2239. https://doi.org/10.1016/j.solener.2021.02.058

CRUSH System Coupling to Concentrated Solar Power on Demand (CSPond) System-II

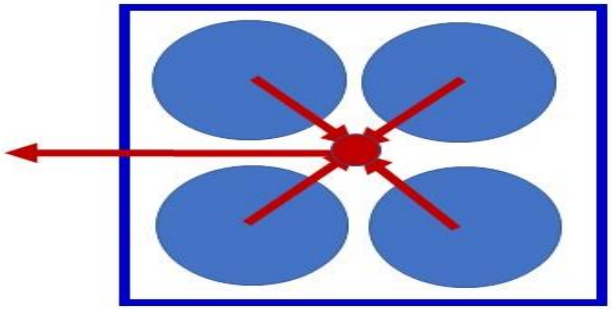
- Addresses concerns about rock impurities in solar collector from CRUSH system
- Small prototype facility successfully tested concept
- For CRUSH, hot salt from multiple CSPonD systems sent to CRUSH and power block



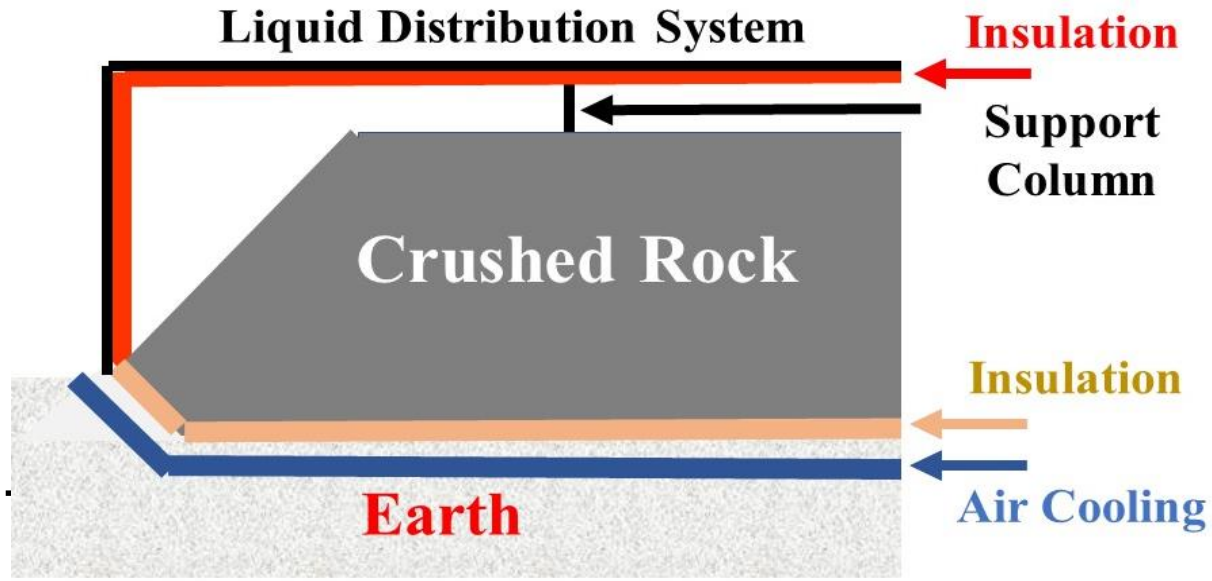
Large-Scale CSP Questions



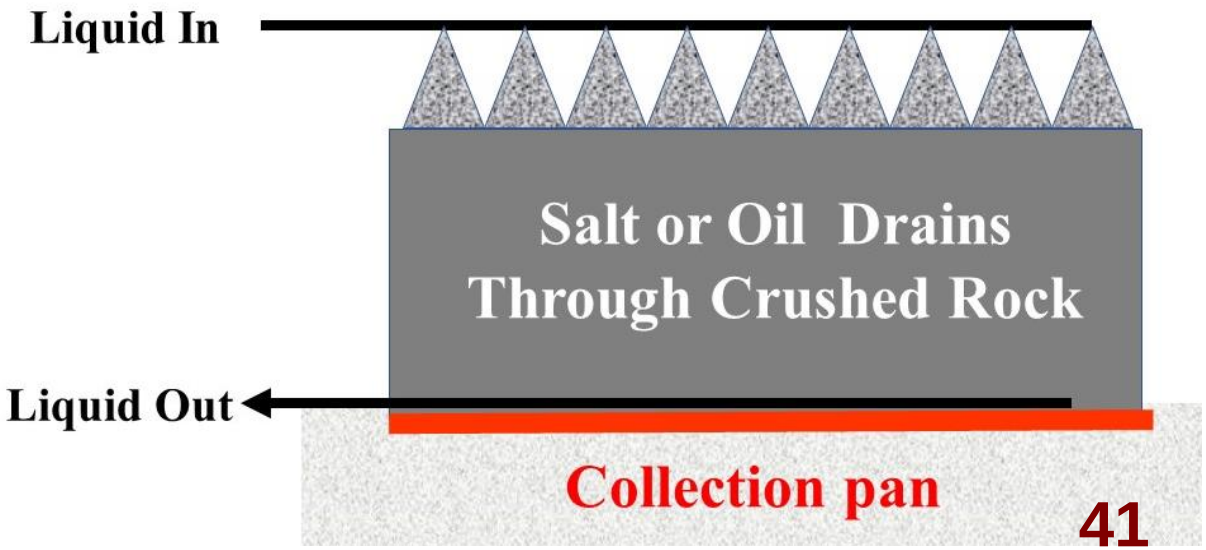
Pipeline from Multiple Towers



Insulated Roof with Liquid Distribution System



Nitrate Salt or Oil Spray System



CSP/CRUSH System Conclusions

- **With large-scale solar deployment, economics is more dependent on the cost of storage than cost of solar**
- CRUSH system is much less expensive than electricity storage with incremental capital-cost goal of $2-4/kWh of heat
- Modify CSP with multiple plants to central CRUSH/power block to couple to low-cost storage and power block to enable lower cost solar with greater revenue

Heat-Transfer Oil Versus Nitrate Salt CRUSH Systems

Heat Transfer Oil vs. Nitrate Salt

- Heat transfer oil
  - More expensive
  - Peak temperature ~ 400C
  - Little interactions with most types of crushed rock
- Nitrate salts
  - Relatively inexpensive
  - Peak temperatures approach 600C
  - Require careful rock selection for compatibility

Compatibility of Different Rocks with Nitrate Salts-1

Rock category	Rock type	Chemical Composition	Mineral Composition
Igneous	Microgranite	SiO_2 (65% ~ 70%), a little of Al_2O_3, CaO, MgO and Fe_2O_3	Quartz
	Gabbro	48.6% SiO_2, 12.1% CaO, 9.4% Al_2O_3, 9.9% MgO, 9% Fe_2O_3.15% TiO_2	Labradorite and pyroxene
	Coarse grained granite	SiO_2 (65% ~ 70%), a little of Al_2O_3, CaO, MgO and Fe_2O_3	Feldspar, quartz, a few dark—coloured mineral, sand, mica.

Good, Maybe, Poor

Compatibility of Different Rocks with Nitrate Salts-2

Rock category	Rock type	Chemical Composition	Mineral Composition
Sedimentary	Taconite	Quartz (55–60%), followed by smaller amounts of iron oxides, carbonates, and silicates	Iron minerals are interlayered with quartz, chert, or carbonate
	Calcareous sandstone	70% SiO_2, 29% CaO and 1%Fe_2O_3	Quartz grains and carbonates
	Limestone	35% $CaCO_3$, 16% MgO and trace amounts of SiO_2, Al_2O_3, Fe_2O_3, SO_3, K_2O and Na_2O	Calcite and dolomite

Good, Maybe, Poor

Compatibility of Different Rocks with Nitrate Salts-3

Rock category	Rock type	Chemical Composition	Mineral Composition
Metamorphic	Serpentinite	$Mg3[Si_2O_5](OH)_4$ crystals of magnesium (magnetite) and iron oxides	Antigorite, litardite and chrysotile
	Cipolin	52.5% SiO_2, 20.5% Al_2O_3, 14% CaO, 5.6% Fe_2O_3 and trace amounts of MgO, Na_2O, TiO_2, MnO_2, P_2O_5 and K_2O	Calcite, dolomite, and serpentine
	Hornfels	$(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_22(OH)_2$	Actinolite, andalusite, augite, biotite, calcite, chlorite, cordierite, diopside, epidote, feldspars, garnet, graphite, hornblende, kyanite, pyrite, scapolite, sillimanite, sphene, tourmaline, and vesuvianite.
	Andausite hornfels	63% Al_2O_3, 37% SiO_2	

Backup Viewgraphs

CRUSH Applicable to All Heat Systems

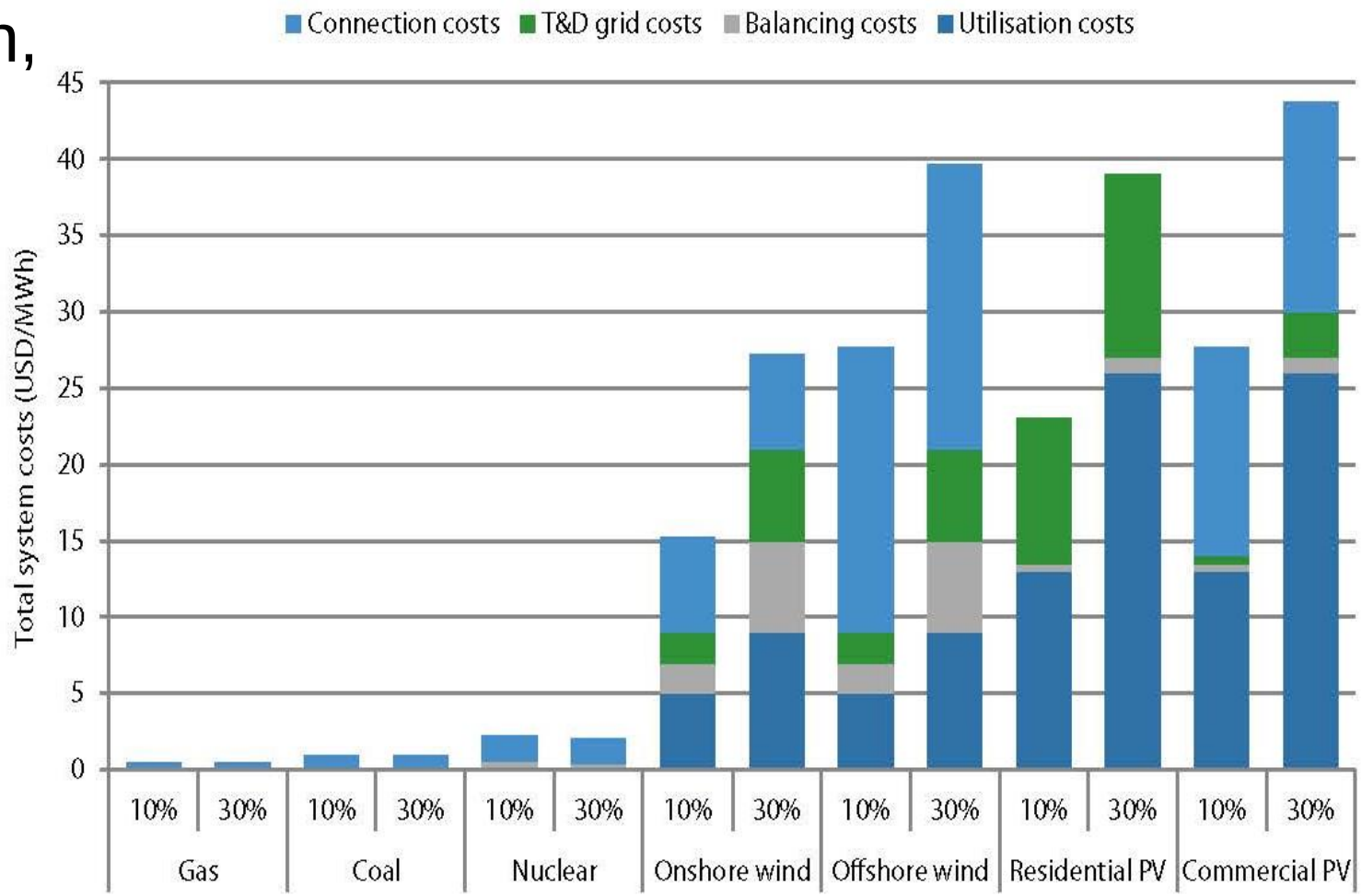
- Nuclear
- All solar systems
  - Classical CSP
  - Direct adsorption of light by heat transfer fluid
  - Photovoltaic with direct conversion to heat
- Conversion of low-price electricity into stored heat for electricity or heat markets

Features to Control Fluid, Building Atmosphere Composition and Minimize Air Pollution

- Filters to remove fine particles in oil or nitrate salt generated by thermal expansion and contraction of rock over time
- Atmospheric control
  - Oil heat transfer. Use inert gas (nitrogen or argon) to minimize oil degradation with time
  - Nitrate salt. Air or controlled atmosphere to minimize degradation of nitrate salt at higher temperatures
- Off-gas system to minimize air pollution and heat losses while maintaining atmospheric pressure (breather bags with/without heat storage or absorbers) as building breaths

CRUSH Can Decrease System Solar Costs

- At higher penetration, solar system costs rise dramatically
  - Transmission
  - Backup electricity
  - Non-dispatchability
- 100 GWh daily-to-weekly heat storage eliminates many of these costs

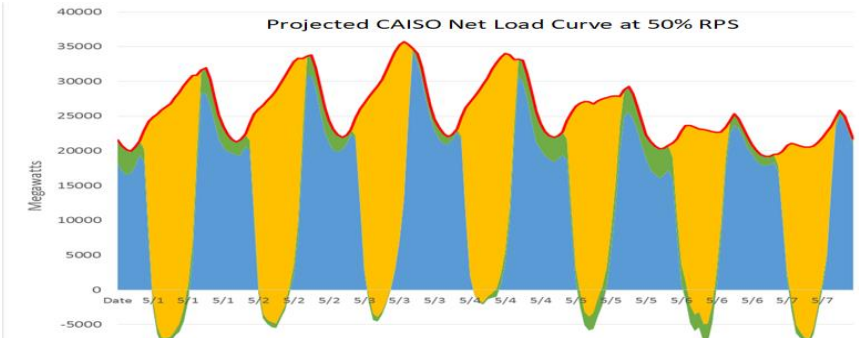


Nuclear Energy Agency, Organization for Economic Co-Operation and Development, The Full Cost of Electricity Provision, NEA No. 7298, 2018

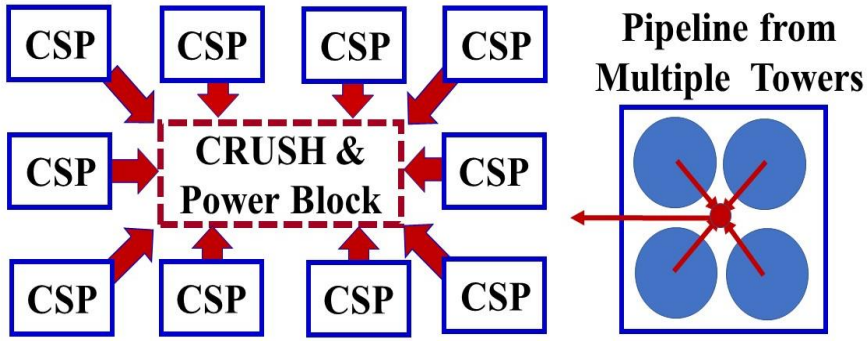
1000-MW CSP with 100-Gigawatt-hour Crushed-rock Heat Storage to Replace Dispatchable Fossil-fuel Electricity

Charles Forsberg, Massachusetts Institute of Technology

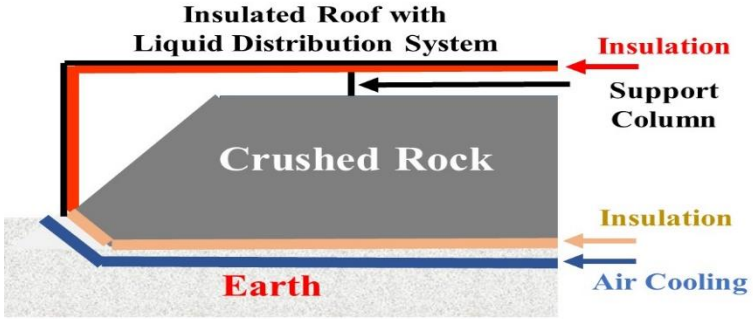
- If large scale solar, cost of storage (not cost of solar) controls electricity prices
- Zero value electricity during the day

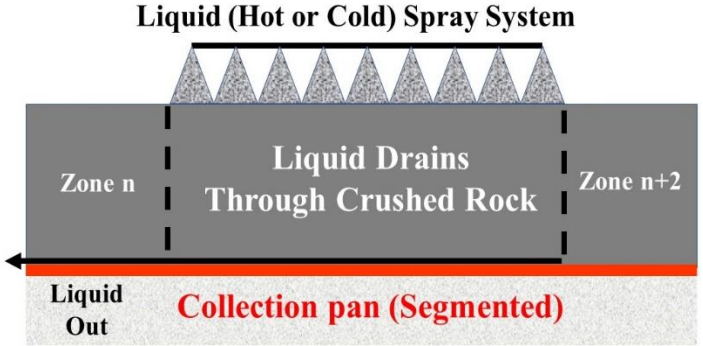


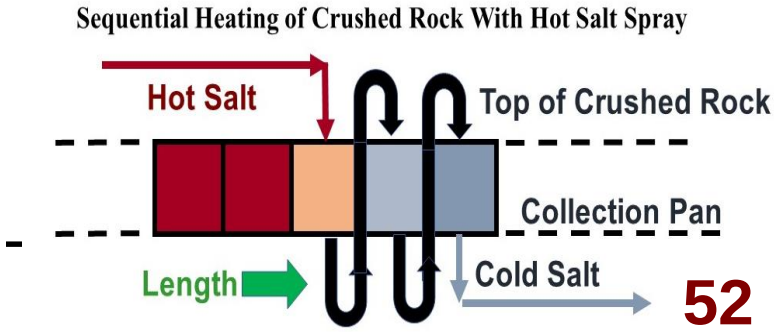
- Cheap storage and power block (right) requires massive solar heat input
- Multiple solar farms send heat to storage via oil or nitrate salt pipelines



- Two-tank (hot / cold) heat storage has two expensive items
  - Tanks
  - Oil or nitrate-salt heat storage material
- Replace oil or nitrate salt with crushed rock pile 20+ meters high
  - Hot or cold oil or salt from solar collector sprayed on top of crushed rock
  - Gravity flow to collection pan below crushed rock—minimize oil or salt
  - Sequential heating / cooling of rock
- Replace tanks with insulated air-craft-hangar-like building
  - Sloped rock so no pressure on walls
  - Low conductivity road bed foundation under crushed rock with salt drains
  - Air cooling under road bed
- Cost goal of $2-4/kWh of heat
  - Require large size for low cost to minimize surface (building) to volume (heat storage) ratio
  - 10 to 100 GWh capacity
  - Factor of 50 under batteries per unit of electricity

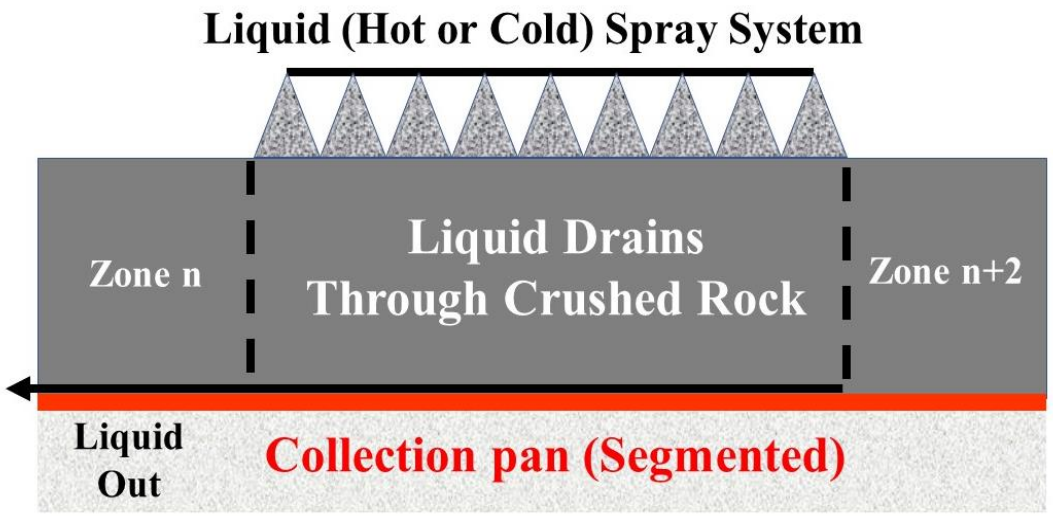


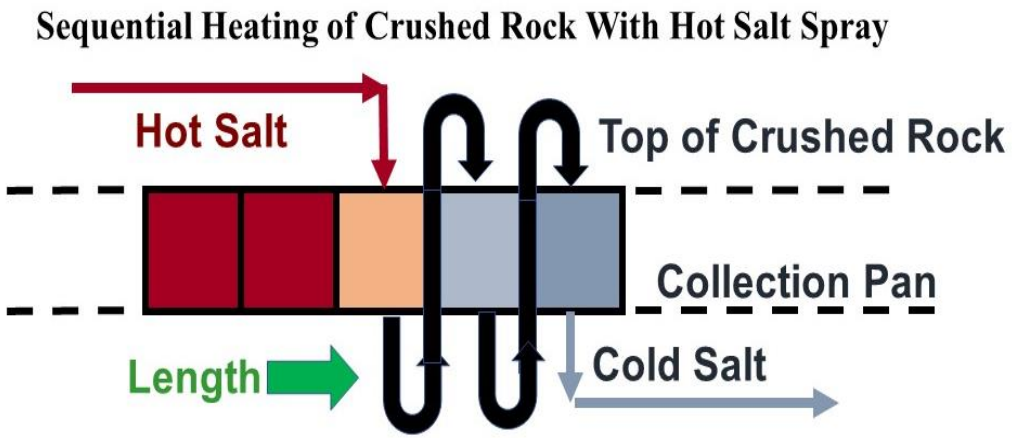




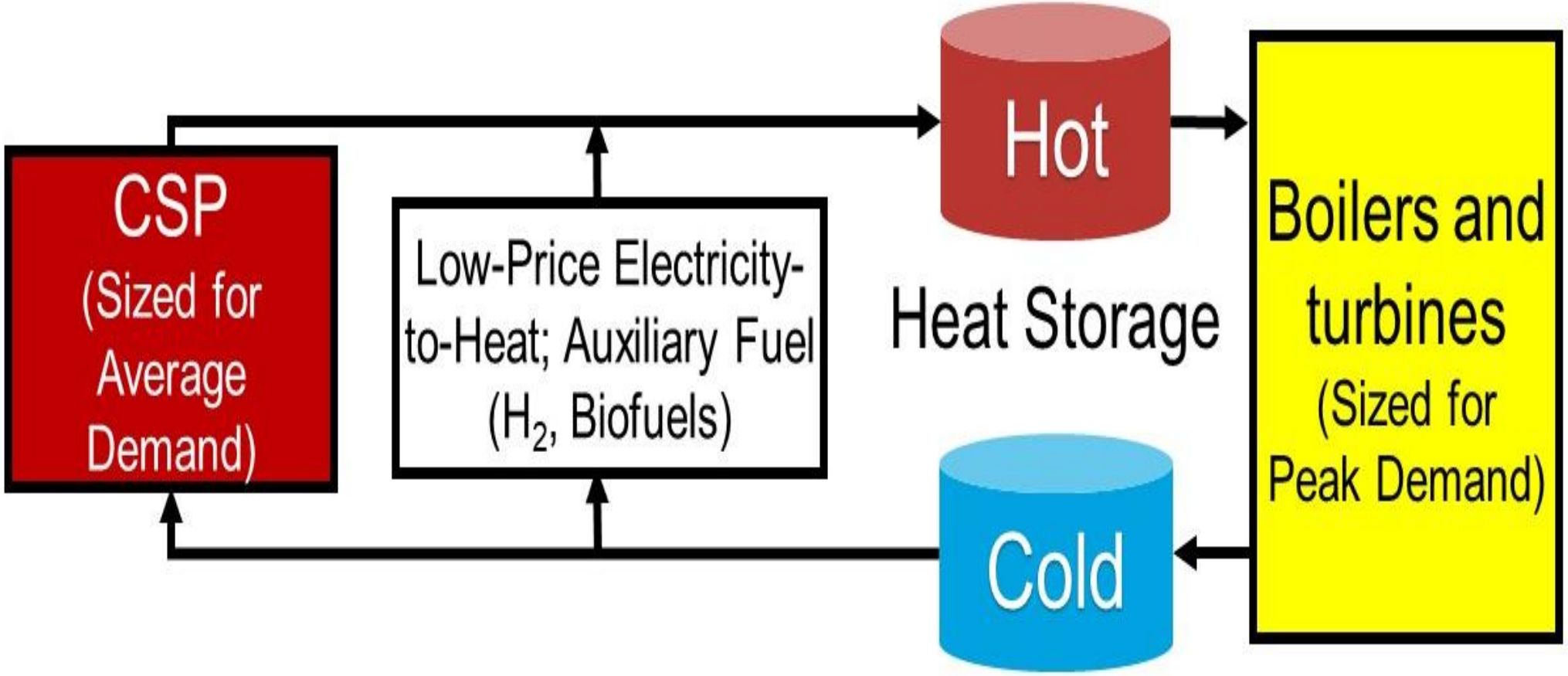
CRUSH Addresses Non-Uniform Heating

- Sequential heating of crushed rock sections left to right
- Similar to heap leaching of copper ores (mass transfer) except heat transfer by fluid flow <u>and heat conduction</u>
- Partly addresses challenge of non-uniform heat transfer or bypass flow in crushed rock

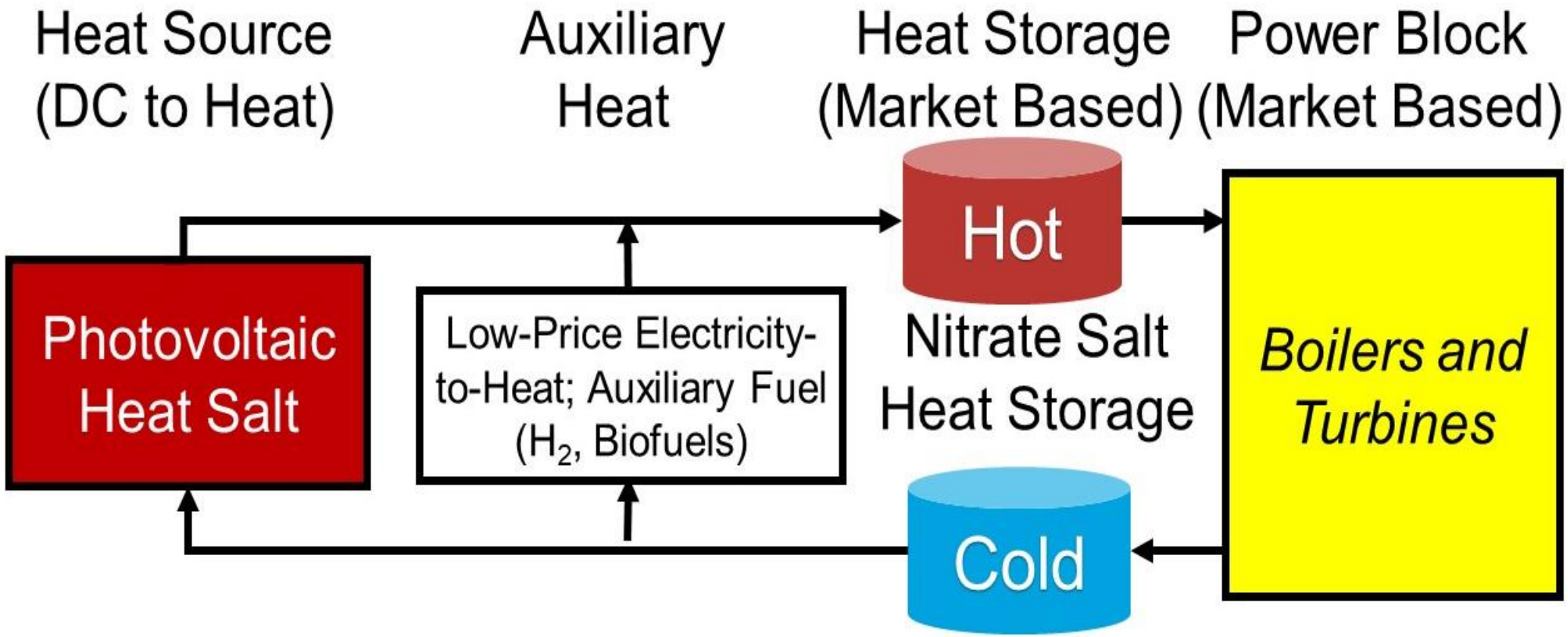




System Design of CSP System with Storage



Require Rethinking Solar PV with Heat Storage



C. W. Forsberg, P. Sabharwall and A. Sowder, Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm, Workshop Proceedings, ANP-TR-189, Massachusetts Institute of Technology, November 2020. https://www.osti.gov/biblio/1768046

CRUSH Heat Storage is Similar to Heap Leaching of Low-Grade Copper, Uranium and other Ores—20% Global Copper Production

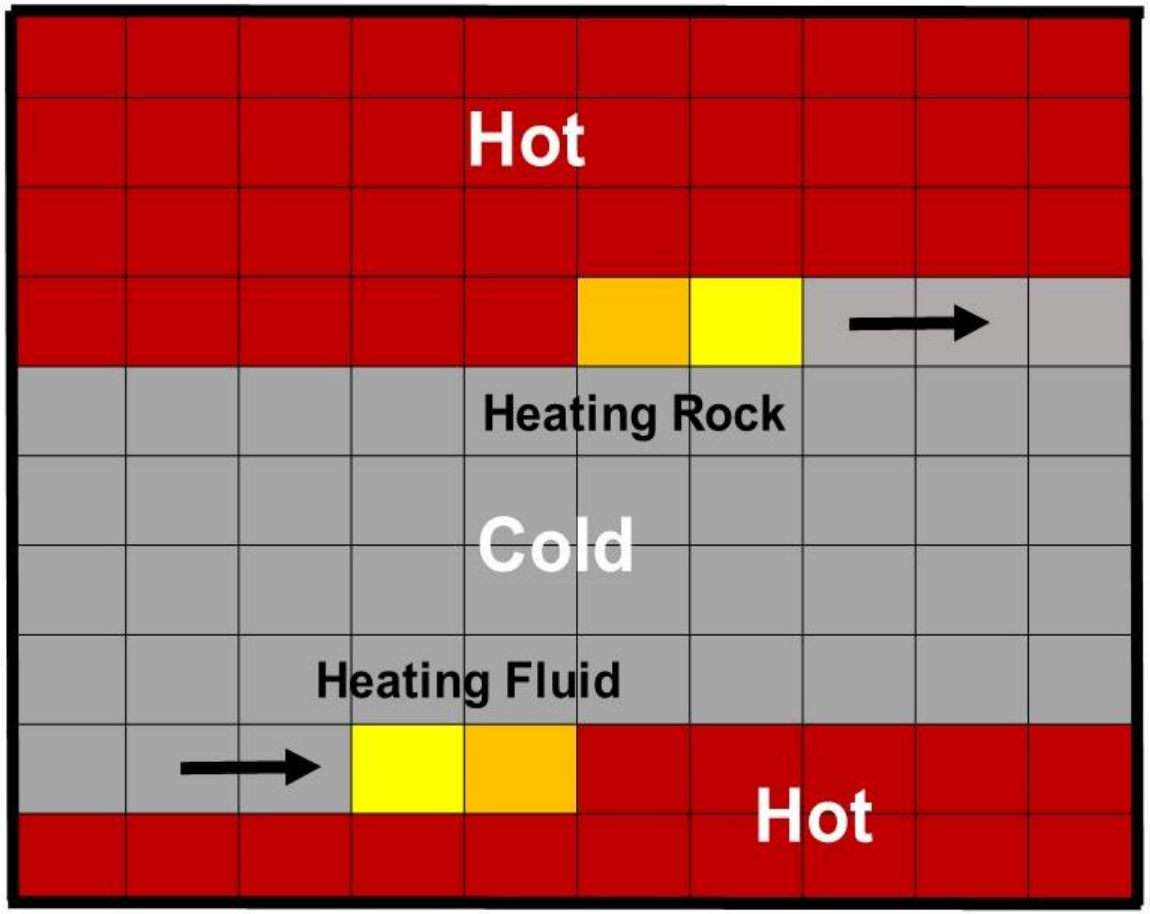
- Spray liquid on top of crushed ore
- Gravity flow through crushed rock to drain pan
- Liquid dissolves copper
- Crushed rock 10 to 100 meters high

https://www.csiro.au/en/Research/MRF/Areas/Resourceful-magazine/Issue-07/bugs-boost-leaching

Minimize Container Cost By Minimizing Surface-to-Volume

Rock Pile 20 m by 250 m by 250 m or Larger (100GWh)

- 25 m by 25 m heating and cooling zones
- Crushed rock without flowing salt acts as a partial insulator
  - Low-conductivity crushed rock—touch at points
  - Gas between rocks acts as insulator



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