NATIONAL RENEWABLE ENERGY LABORATORY

Gen3 CSP: U.S. and Australian Cooperative Research on 700°C Heat Transfer Systems

Asia-Pacific Solar Research Conference
Sydney, Australia
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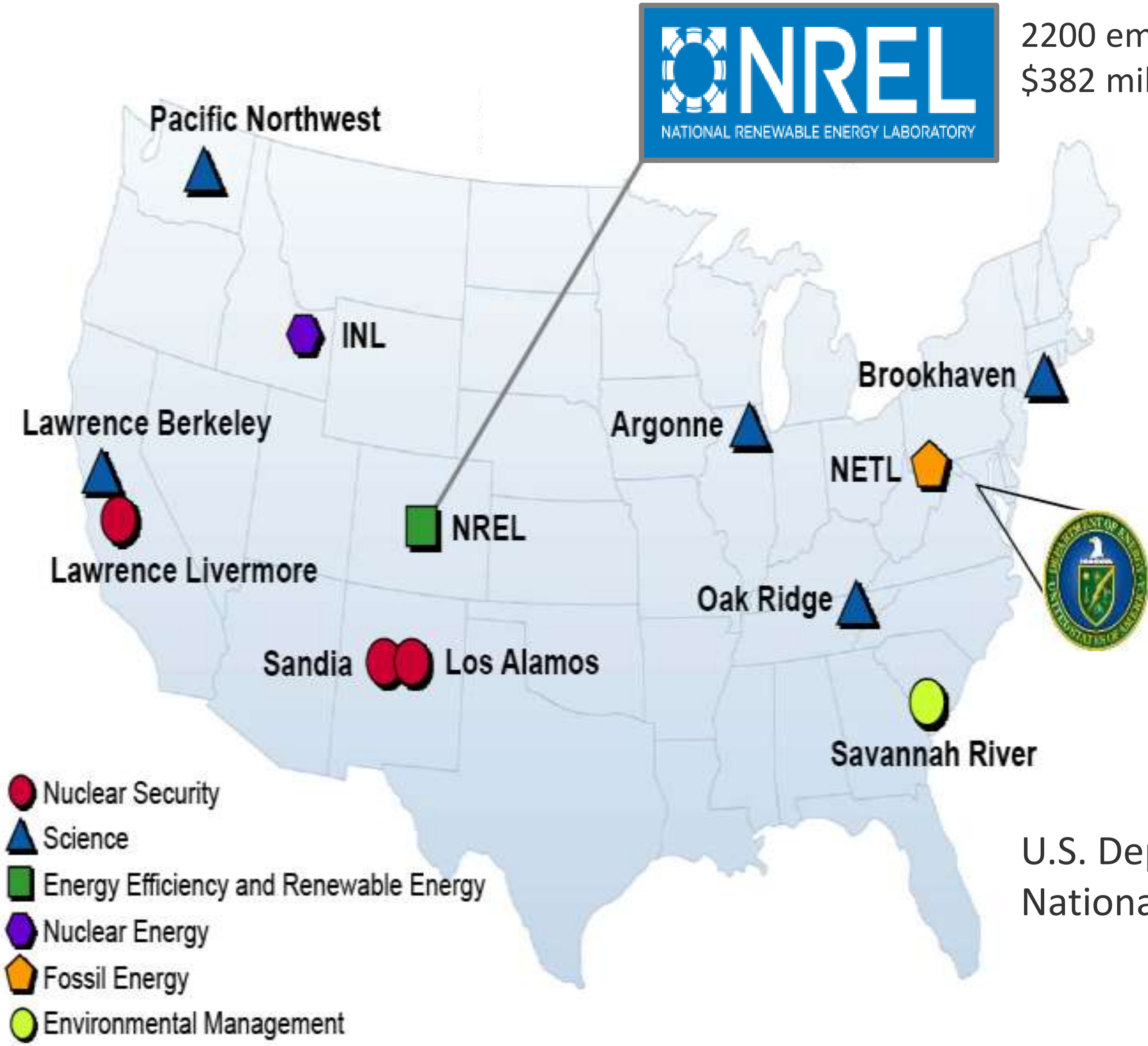
Crescent Dunes Solar Energy Facility, USA

National Renewable Energy Laboratory

2200 employees
$382 million USD



U.S. DOE

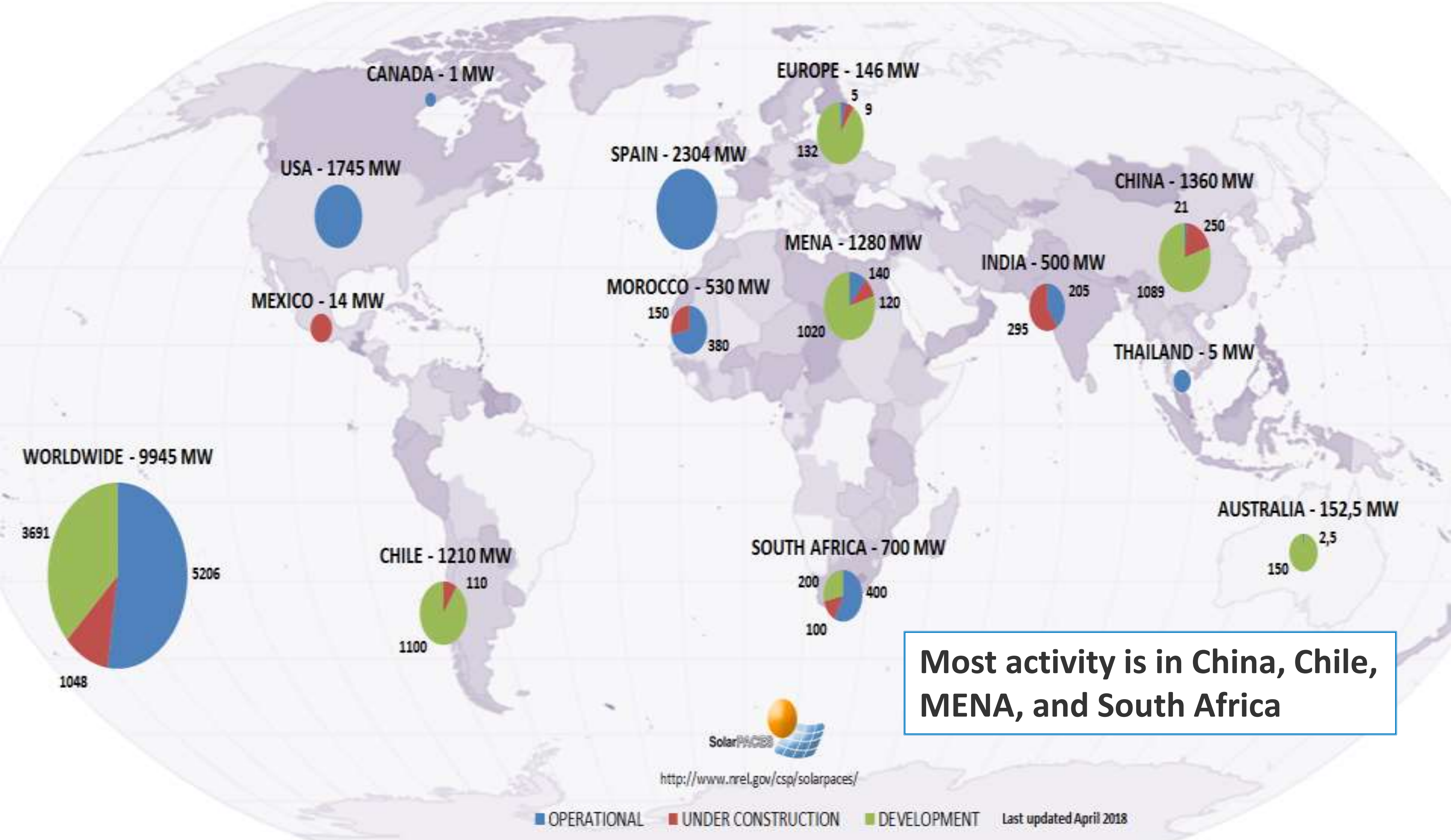
U.S. Department of Energy's National Laboratory System

Outline

- CSP in the world today
- CSP's value proposition
- USA's CSP Gen3 program
- USA/Australia partnership
- Liquid Pathway to CSP Gen3

Morocco's 510 MW Noor Solar Complex at Ouarzazate
(photo credit SolarPACES and SENER)

CSP Around the World



Most activity is in China, Chile, MENA, and South Africa

CSP Project Activity

Several recent projects have reported record low power-purchase prices for CSP.

DEWA IV, Dubai
- 700 MW
- 10+ hours of Storage
- 0.073 USD/kWh

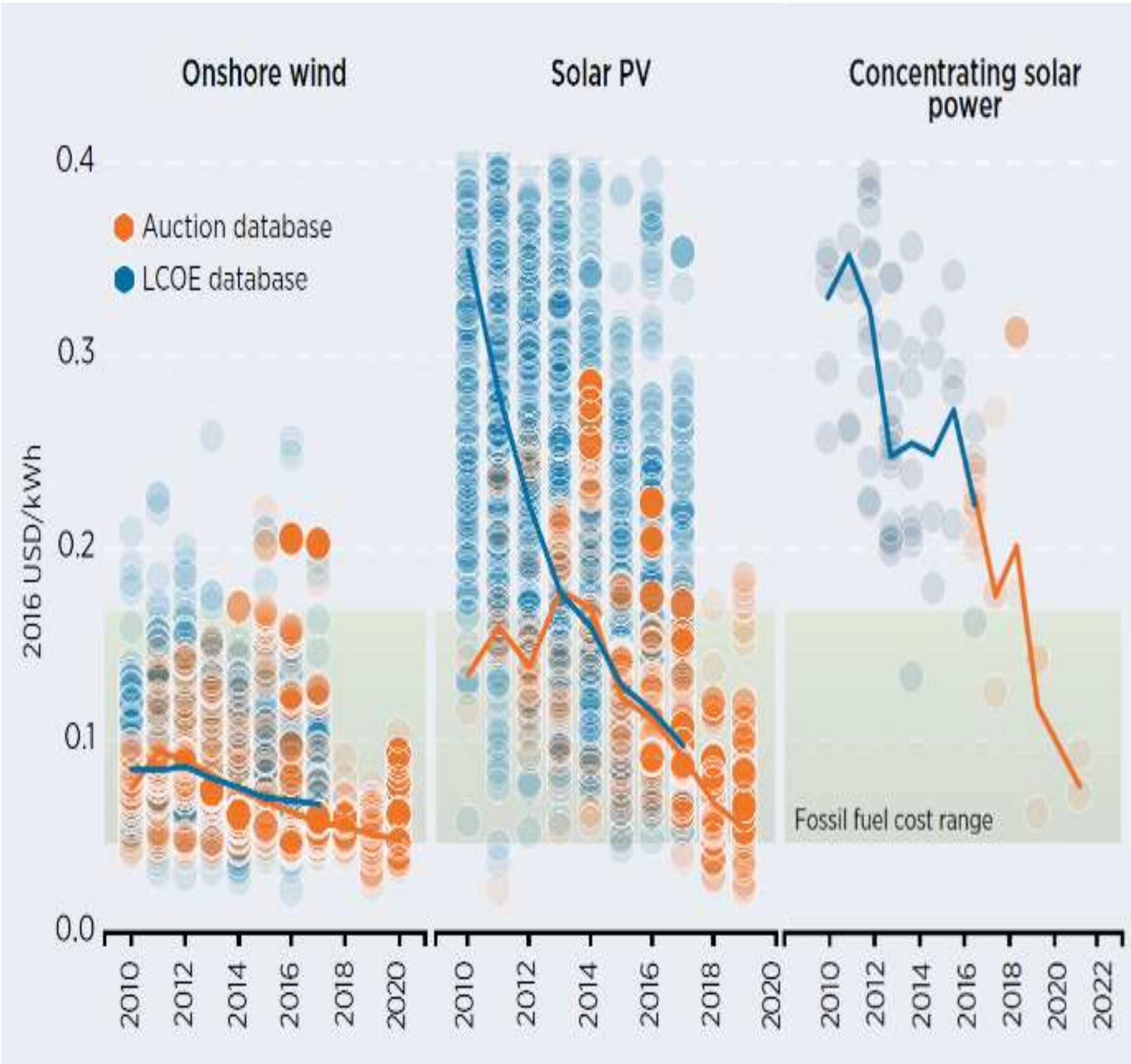
Aurora, Australia
- 150 MW
- 8 hours of Storage
- 0.061 USD/kWh

Chile
- 13 hours of Storage
- < 0.05 USD/kWh

Lilliestam & Pitz-Paal 2018

CSP Today Feb. 20, 2018

Wind and Solar Cost Trends



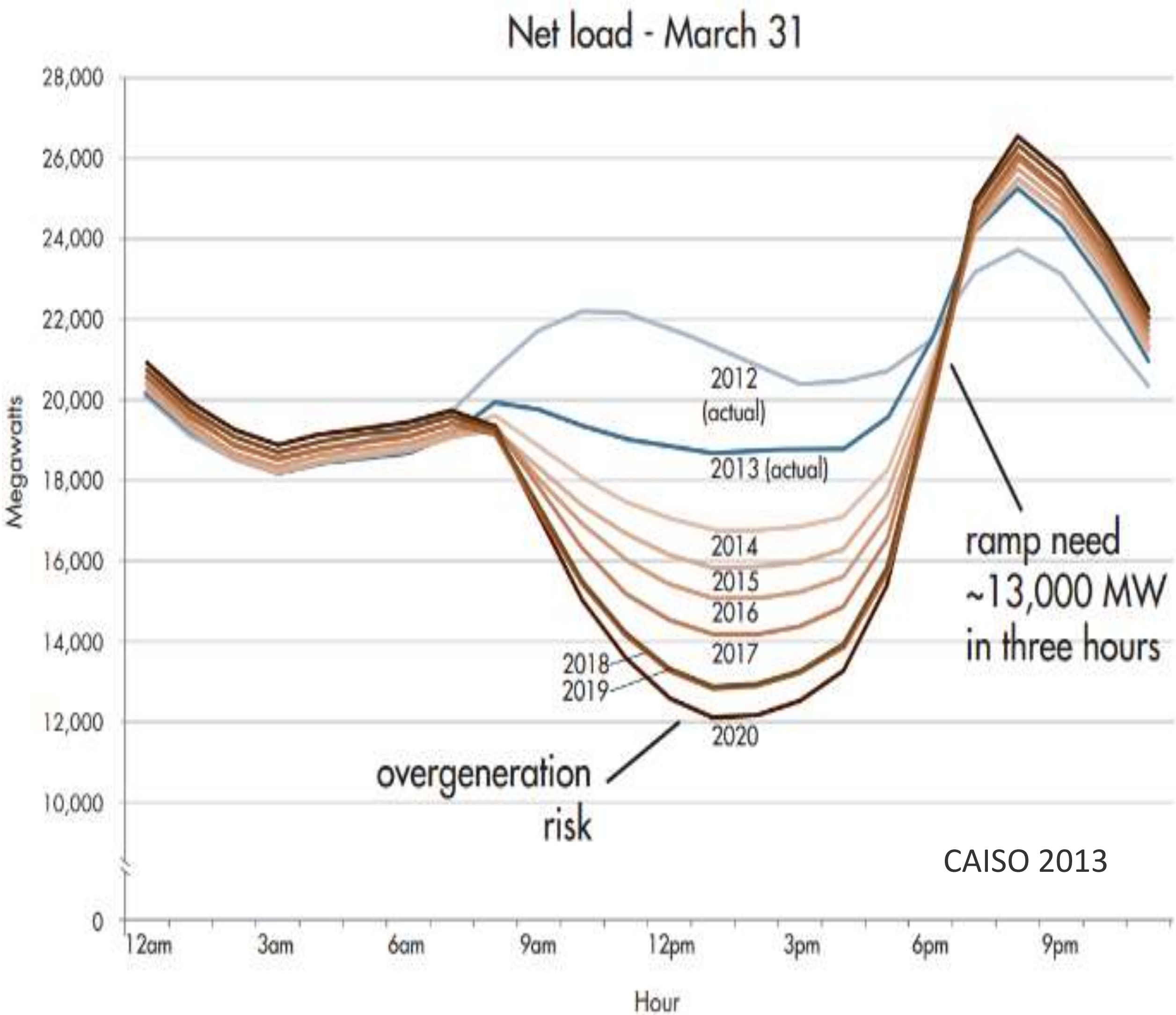
While Wind, Solar PV, and Solar CSP have all seen dramatic cost reductions, CSP cannot match the low energy cost of Wind and PV.

Source: Michael Taylor, IRENA. *IRENA Renewable Cost Database and Auctions Database*

Molten-salt storage tanks at a CSP plant in Spain.

The relevance of CSP relies on the ability to provide renewable energy when needed, not just when available. In short, thermal energy storage providing solar power on demand is the role of CSP.

The California “Duck Curve”



CAISO 2013

Growing solar PV penetration in the CAISO grid continues to suppress residual (non-solar) load in mid day, thus forcing large ramping in morning and evening.

CSP's Potential in the Future U.S. Electric Grid

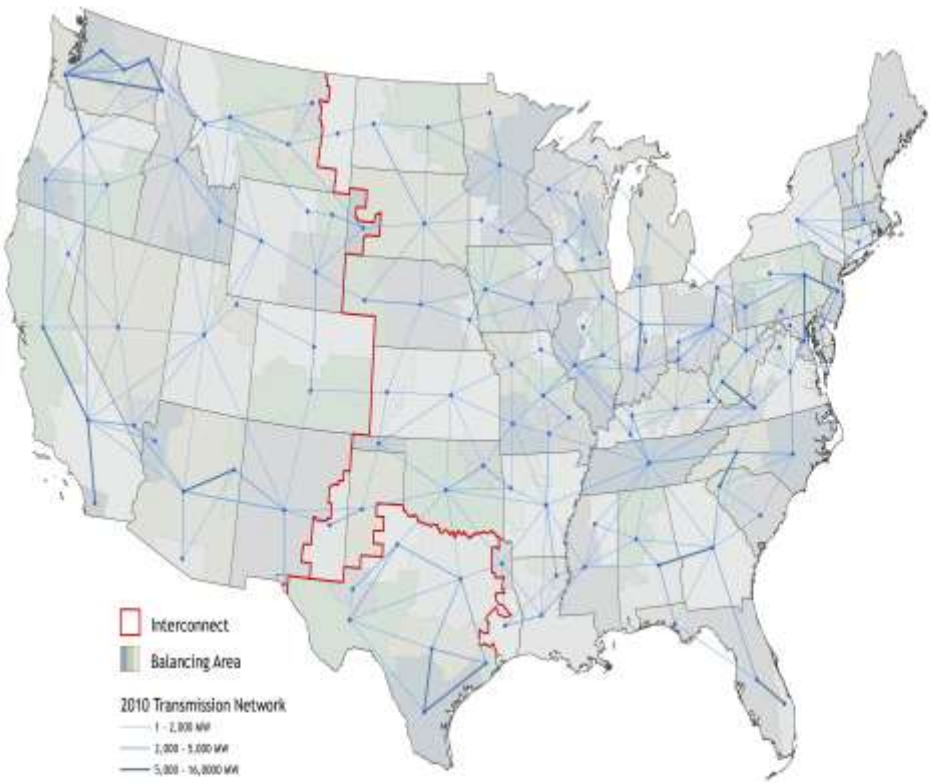
The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets

C. Murphy, Y. Sun, W. Cole, G. Maclaurin, C. Turchi, and M. Mehos

Note: All data and results are preliminary and subject to change

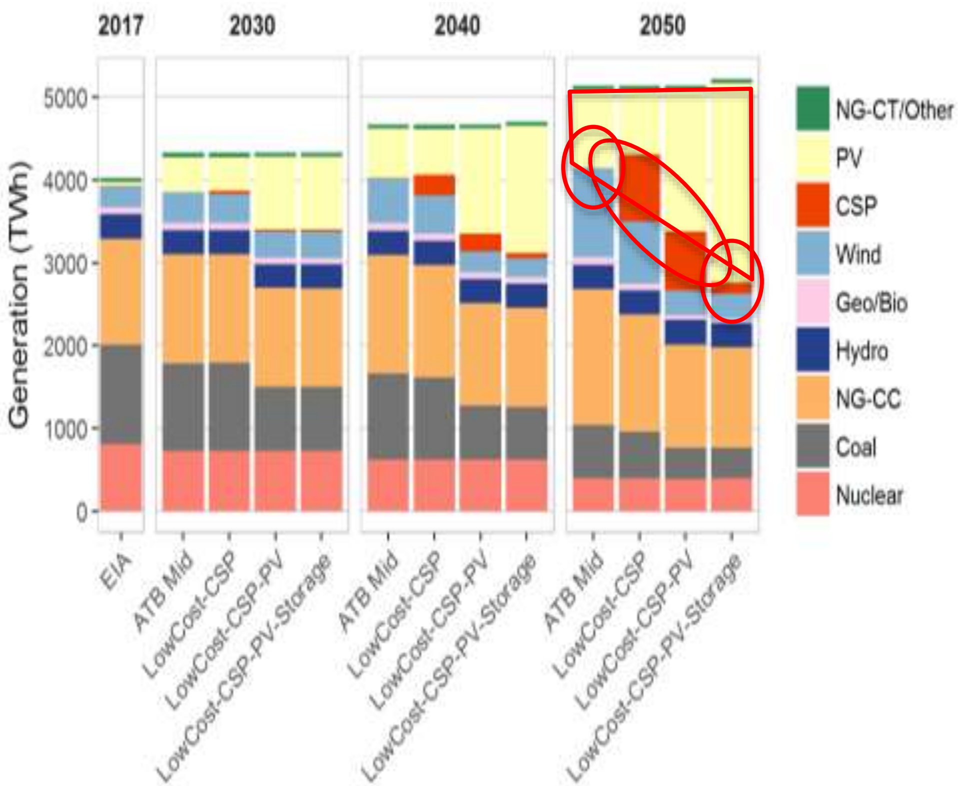
NREL's Capacity Expansion Modeling

Regional Energy Deployment System (ReEDS) model



- Capacity expansion model to simulate expansion and operation of the US generation and transmission systems through 2050
- 134 balancing areas for electricity; 356 renewable resource regions
- 17 time slices within a year to characterize annual load shape
- Key outputs: generation, capacity, costs, fuel use, and emissions

Generation Projections (USA)

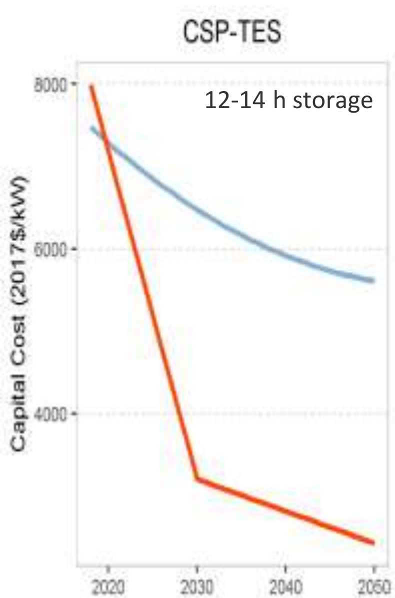


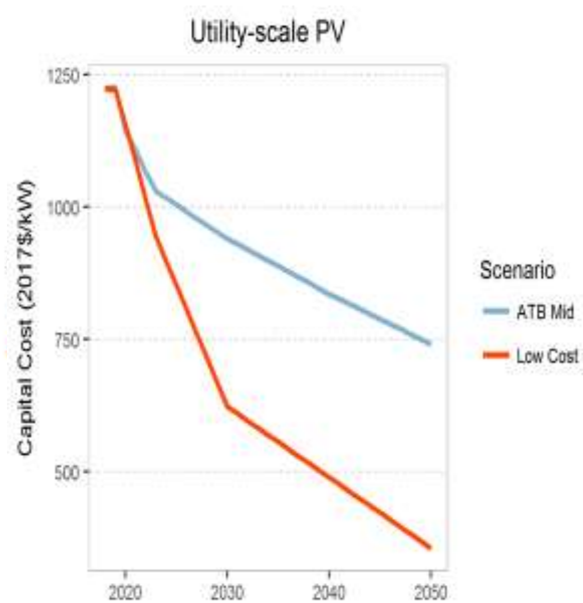
- Without cost reduction, little CSP deployment is predicted
- PV plays an increasing role through 2050 in all scenarios, with 2x to 3x more expansion if *LowCost PV* is achieved;
- *LowCost-CSP* and *LowCost-CSP-PV* trajectories show CSP-TES appearance in the 2030 and steady growth through 2050;
- If all technologies hit low cost targets (*LowCost-CSP-PV-Storage)*, synergies between batteries and PV lead to increased deployment of both, largely at the expense of CSP.

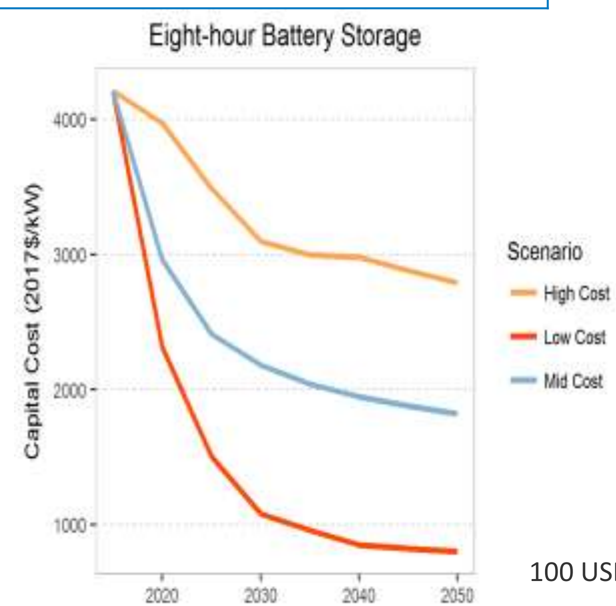
Preliminary Results—Do Not Distribute or Cite

Model Scenario Design & Cost Inputs

Scenario	CSP Cost	PV Cost	Battery Cost
"ATB Mid"	ATB Mid	ATB Mid	Mid Cost
"LowCost-CSP"	Low Cost CSP	ATB Mid	Mid Cost
"LowCost-CSP-PV"	Low Cost CSP	Low Cost PV	Mid Cost
"LowCost-CSP-PV-Storage"	Low Cost CSP	Low Cost PV	Low Cost







100 USD/kWh

Source: Cole et al. 2017; DOE, 2017; Cole, Marcy et al. 2016; ATB = Annual Technology Baseline

USA’s CSP Gen3 Program

In May 2018, the U.S. Department of Energy announced awards totaling $79 million for the CSP Gen3 program.

U.S. Department of Energy, https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp

Evolution of CSP Technology

Generation 3
2020s

- Power Tower
- Molten Liquid? Particles? Gas?
- 12+ hours storage
- Supercritical-CO_2 power cycle with 50% efficiency

Generation 2
2010s

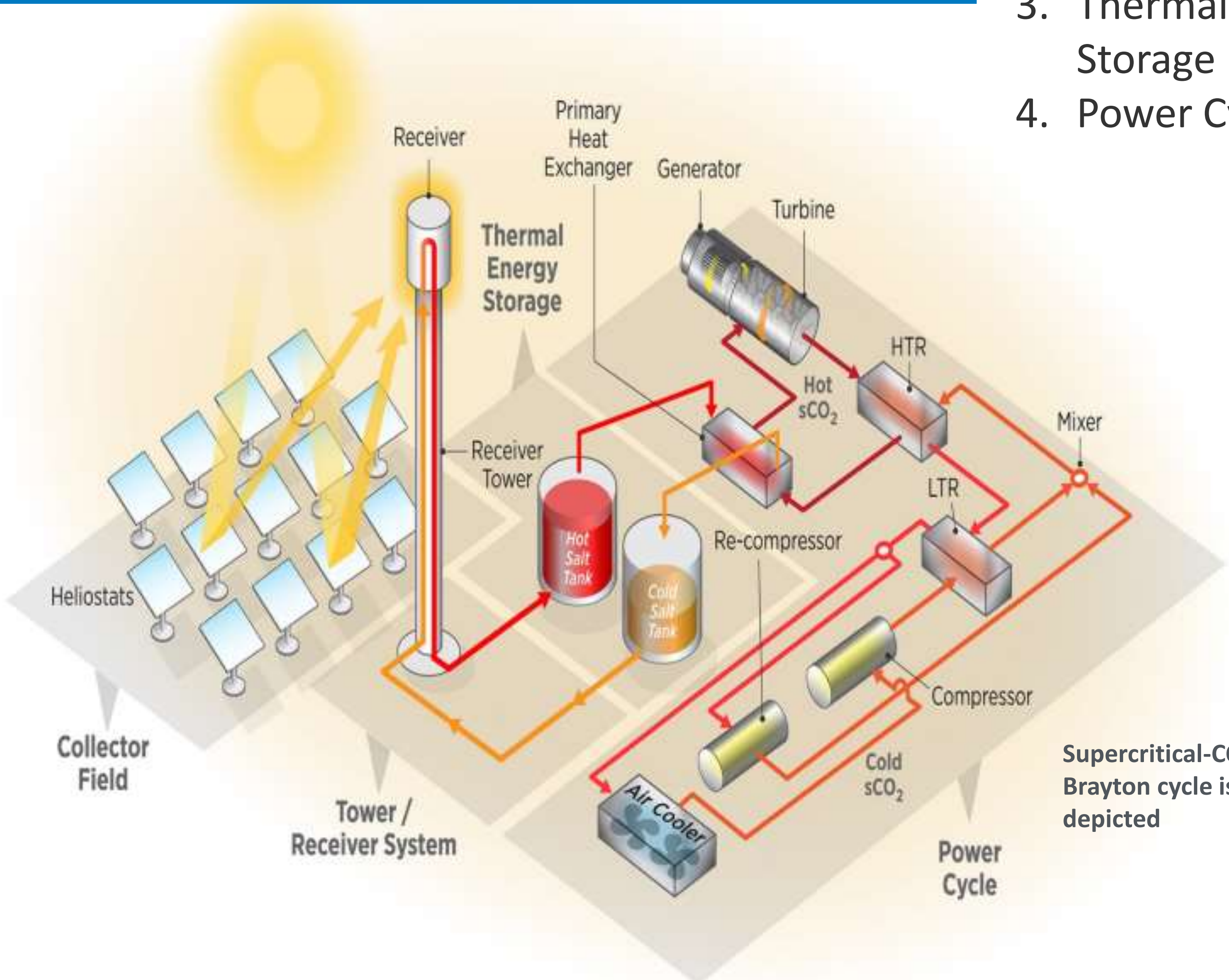
- Power Tower
- Molten Salt in receiver
- 10 hours storage
- Steam power cycle with 42% efficiency

Generation 1
1990s-2000s

- Parabolic Trough
- Thermal Oil in receiver
- No storage
- Steam power cycle with 38% efficiency

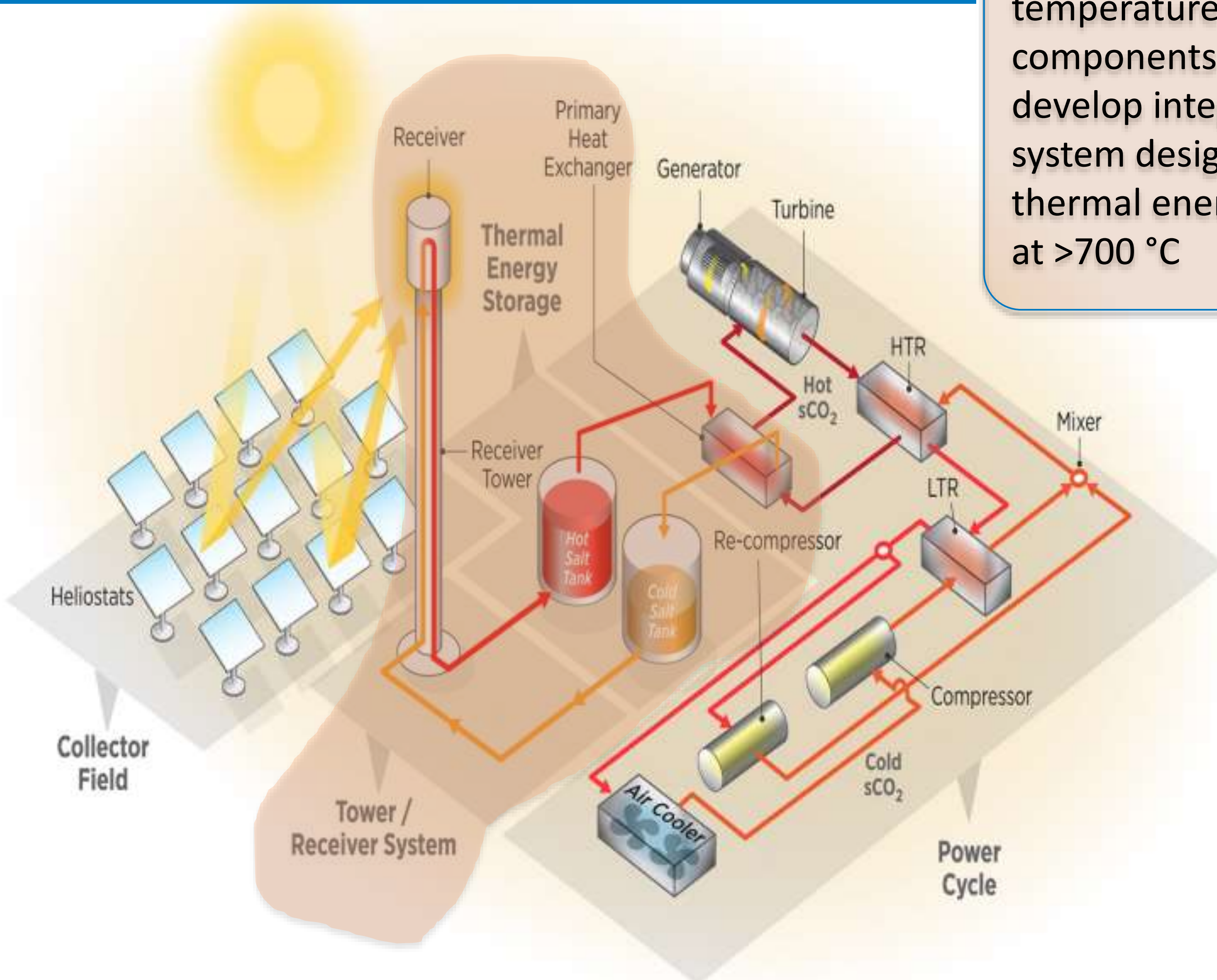
CSP Plant Subsystems

1. Collector Field
2. Tower/Receiver
3. Thermal Energy Storage
4. Power Cycle



Supercritical-CO_2 Brayton cycle is depicted

Gen3 Program addresses the Thermal Transfer Systems



Goal:
De-risk high-temperature components and develop integrated-system designs with thermal energy storage at >700 °C

NREL-led Project: Liquid Pathway

- Leverage expertise with liquid-HTF towers
- Examine two, alternative high-temp liquids
- Use low-cost, thermally stable energy storage media
- Design for sCO_2 Brayton-cycle integration

Vast Solar Jemalong
Sodium-HTF pilot facility (Australia)

SolarReserve Crescent Dunes
Molten-salt HTF plant (USA)

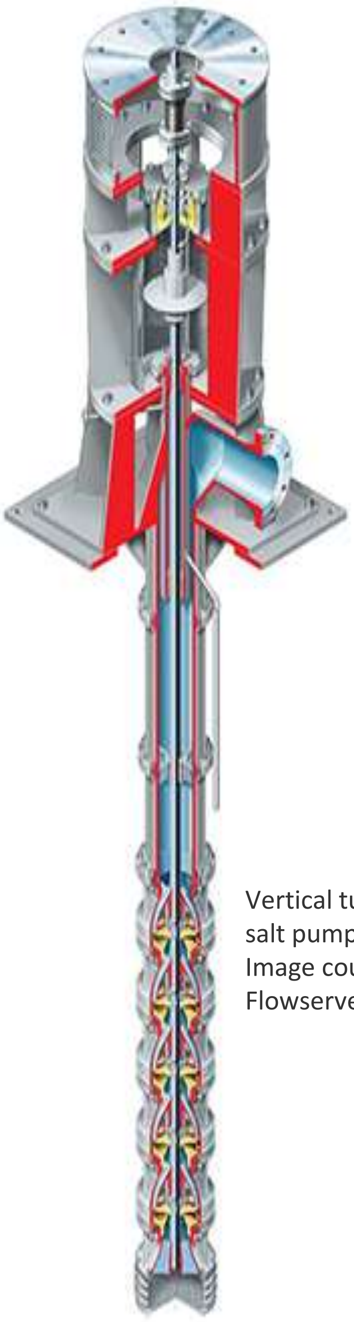
Two Heat Transfer Fluid (HTF) Alternatives

Parameter	Solar Salt (Gen2)	Chloride Salt*	Sodium
Mass composition	60% $NaNO_3$ 40% KNO_3	16% NaCl, 37% KCl 47% $MgCl_2$	100% Na
Stability Limit (°C)	600	>1400	>880
Solidification Temp (°C)	238	400	98
Density (kg/m^3)	1770 @ 500°C	1600 @ 700°C	835 @ 700°C
Specific Heat (J/g-K)	1.53 @ 500°C	1.0 @ 700°C	1.26 @ 700°C
Viscosity (cP)	1.30 @ 500°C	2.4 @ 700°C	0.24 @ 700°C
Thermal Cond. (W/m-K)	0.54 @ 500°C	0.4 @ 700°C	64.2 @ 700°C
Cost ($/kg)	0.8	0.3	3

* Approximate values

Liquid Pathway Advantages

- High heat-transfer rates; low vapor-pressure HTF
- Established approaches for piping, pump, valve, and heat exchanger design (including the receiver)
- High energy and exergy efficiency of storage (direct TES)
  - Flexible dispatch because solar collection and power generation are decoupled
- Recognized and accepted by industry and financiers

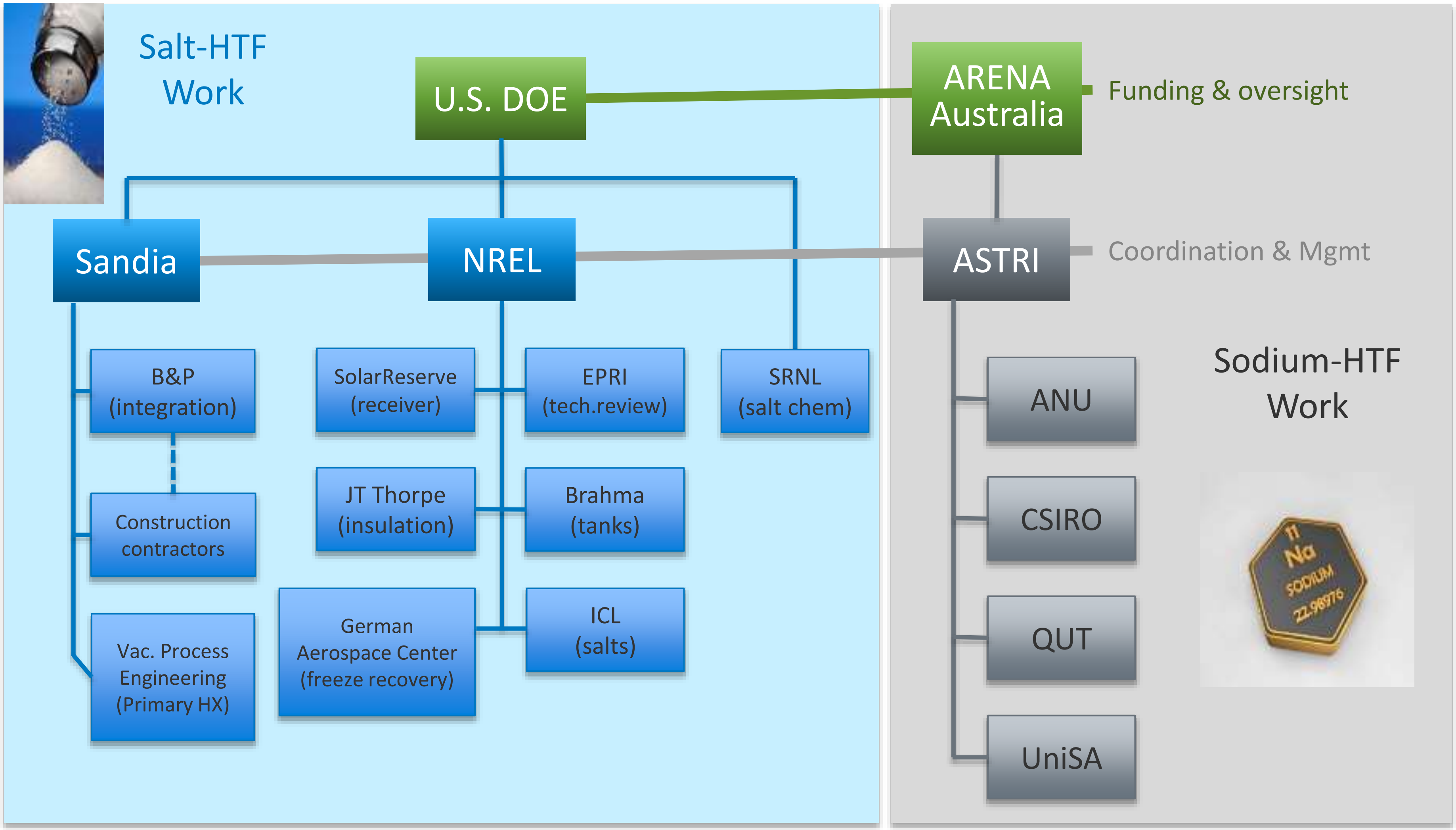


Vertical turbine salt pump. Image courtesy Flowserve.

Liquid-Pathway Challenges

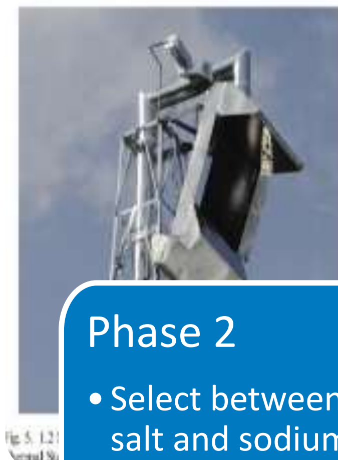
- HTF properties
  - Chloride salt: corrosion control, heat capacity, thermal conductivity, purification & melting, melting point
  - Sodium: reactivity, corrosivity & corrosion control, cost, acceptance
- Containment materials
  - Corrosion resistance, strength at temperature, durability, cost
- Receiver (salt)
  - Efficiency, flux limits, pressure drop, freeze risk, cost
- Thermal Storage (sodium)
  - Design, efficiency, cost
- Operations
  - Startup, shutdown, power ramp rates, heat trace & freeze recovery

Liquid-Pathway Collaboration



3-Phase Project spans five years

Phase 1
- Validate properties
- Select materials
- Design and test critical components



Phase 2
- Select between salt and sodium
- Propose integrated system design

DOE review and pathway selection

Phase 3
- Construction
- Test
- Documention

Integrated System Test in Phase 3

Phase 3 testing planned for Sandia's National Solar Thermal Test Facility

Phase 3 Objectives:

1. Demonstrate effective **corrosion control**
2. Fabricate **cost-effective thermal storage tanks**
3. Operate **solar receiver at 720°C**
   - Confirm efficiency target and heat transfer rates
   - Demo startup, shutdown, and power ramping
   - Define guidelines for receiver operations
4. **Validate pumps**, valves, and piping
5. **Validate primary HX** performance
6. Perform component and system modeling and **simulate full-scale performance**

Summary

- CSP does not compete without thermal energy storage (TES). With TES, it provides dispatchable solar energy (solar on demand).
- However, in the US, due primarily to low-cost natural gas, CSP must achieve lower costs to achieve high penetration in this market
- Gen3 program is designed to demonstrate 700°C thermal transfer and storage systems to enable low-cost CSP
- NREL (USA) is partnered with ASTRI (Australia) to develop and demonstrate a Gen3 system that uses a 700°C liquid thermal transfer system
- Successful Gen3 program leads to predicted 3% to 15% CSP generation contribution to US grid by 2050 (or higher for some carbon-constrained scenarios (not shown).

Thank you

www.nrel.gov

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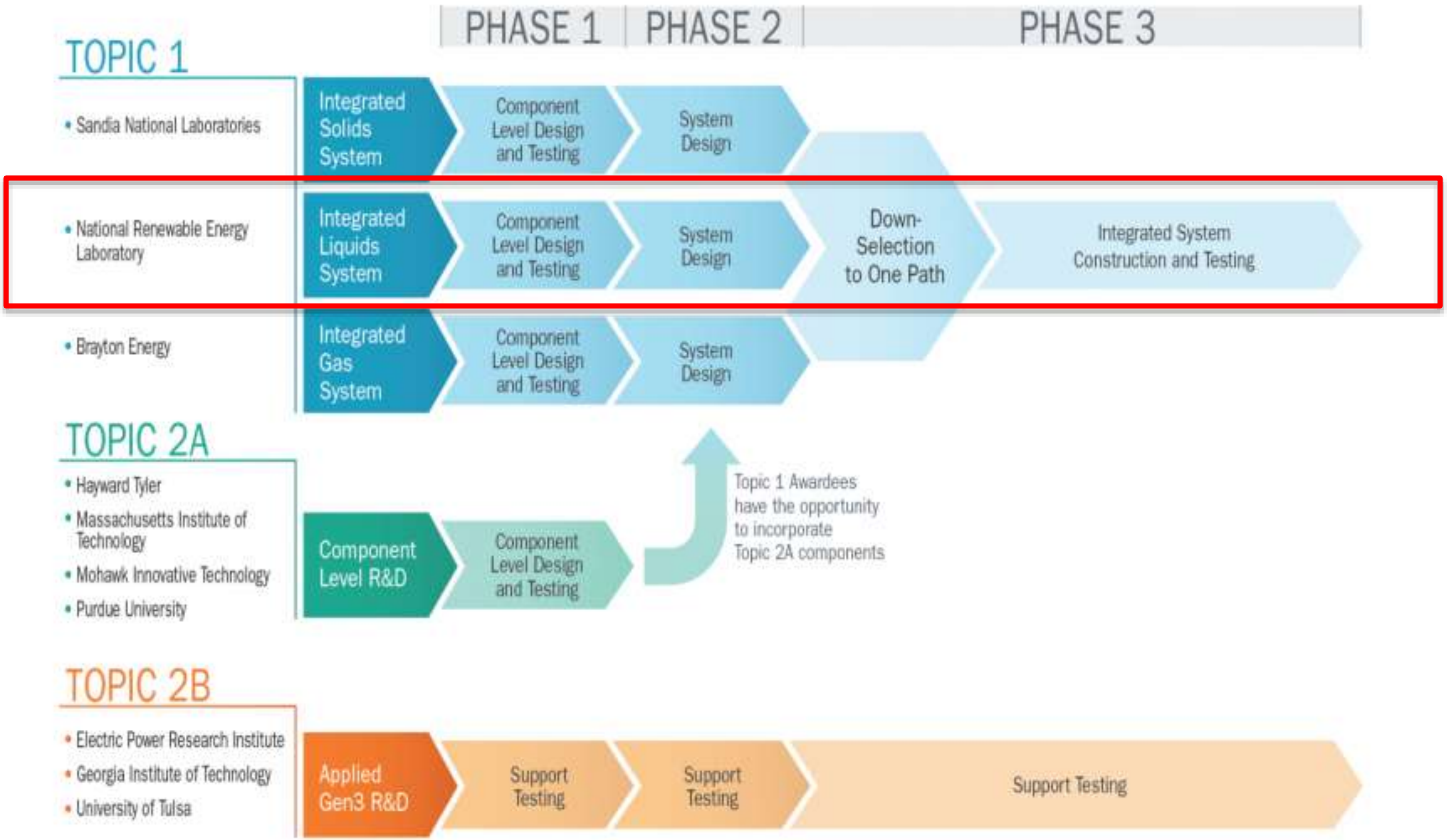
U.S. CSP Gen3 Program



U.S. Department of Energy, https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp

Integrated System Test in Phase 3

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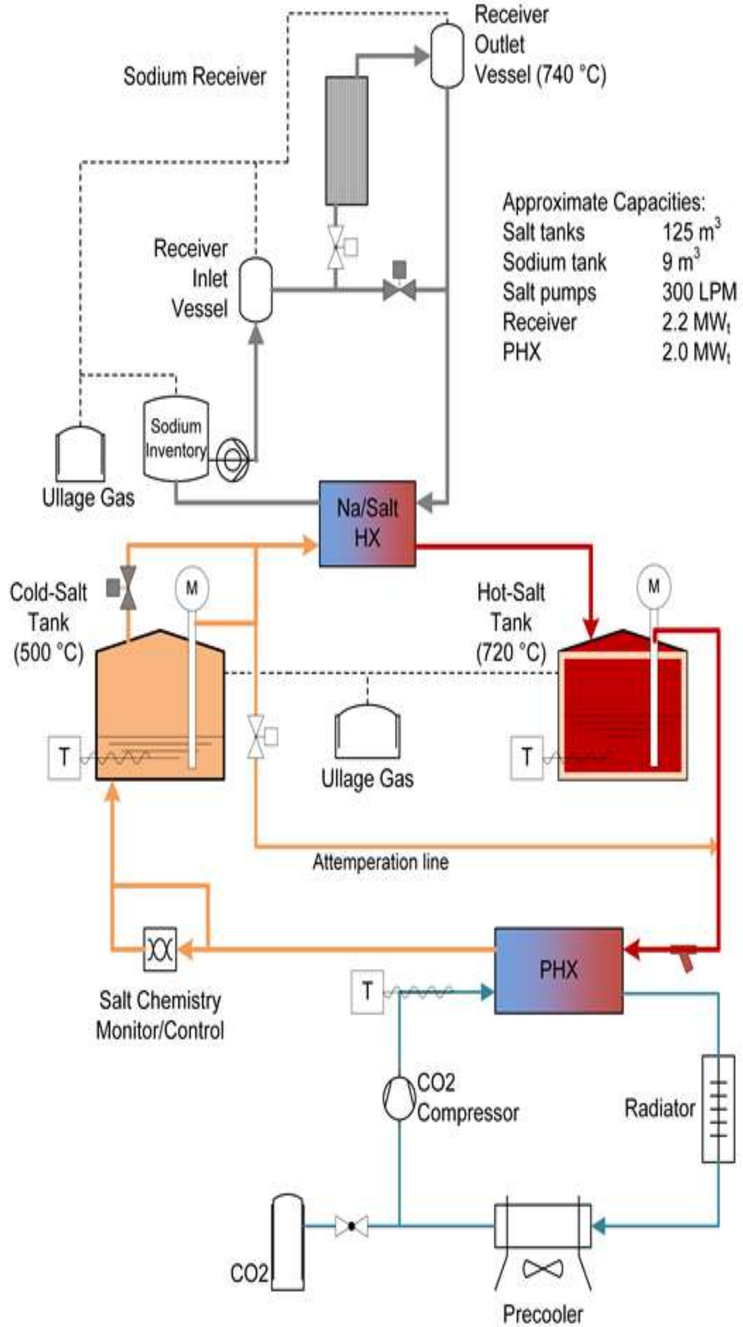


ASTRI Partners

Team Member	Role(s)
NREL	Project management and reporting, Salt receiver design, TES design, corrosion & alloy selection, system analysis
Sandia National Lab	Site Host, Planning and Operations PHX design, project management and on-sun testing (Phase 3)
Savannah River National Lab (SRNL)	Corrosion mitigation and materials selection
Australian National University (ANU) Commonwealth Science & Industrial Research Org. (CSIRO) Queensland Technical University (QUT) University of South Australia (UniSA)	Sodium HTF and salt properties Liquid-sodium receiver, TES design, materials, salt properties, salt/sodium compatibility and heat exchange, solar field/receiver optimization
SolarReserve	CSP Developer: CSP deployment and market analysis
Bridgers & Paxton	Integrator: Facility design, engineering, procurement, and construction
Brahma Group Inc	Tanks

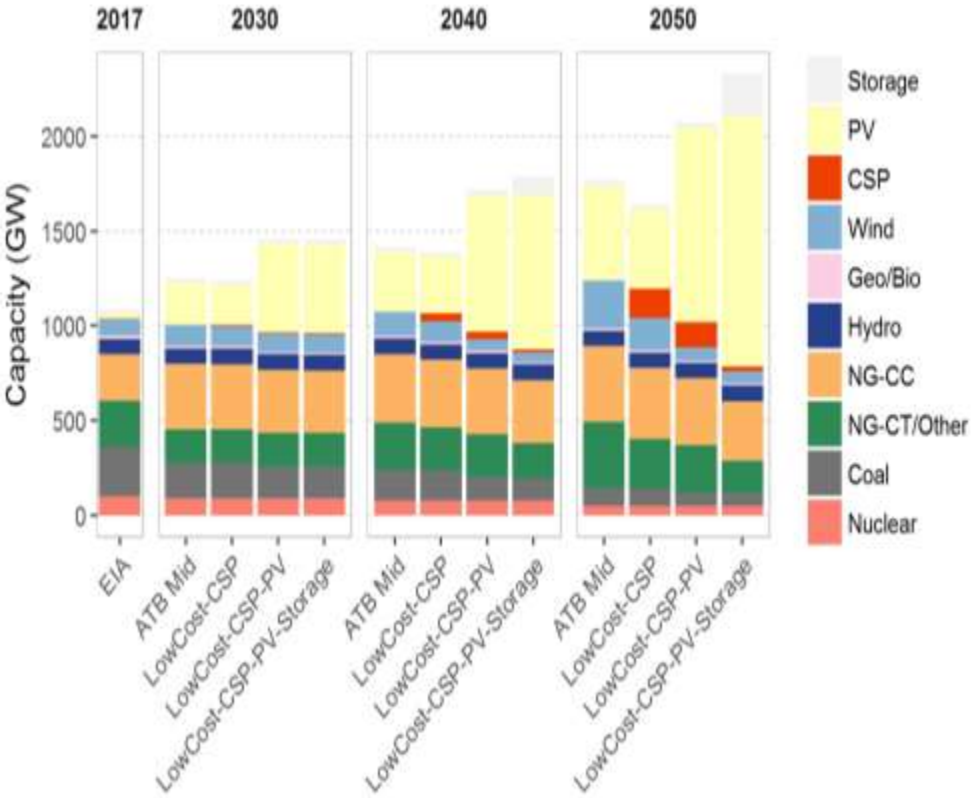
ReEDS Pumped Hydro Storage

- 22 GW PHS current in US grid
- There is 108.7 GW FERC-based PHS resource and 100.5 GW artificial PHS resource in ReEDS.
- FERC-based PHS capital costs are based on O'Connor et al. (2015), and artificial capacity is assumed to be $3,500/kW.
- Under most scenarios, ReEDS builds very little PHS (<1 GW by 2050). However, scenarios that have more VRE penetration can result in higher PHS deployment (~25 GW of deployment, or doubling the size of the current fleet).

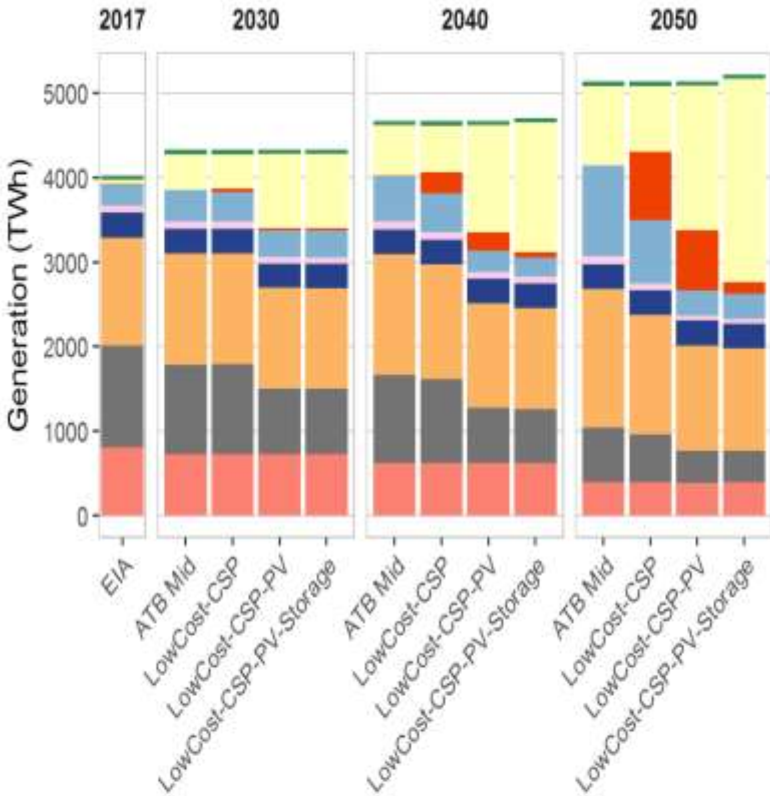
Source: Regional Energy Deployment System (ReEDS) Model Documentation: Version 2016, NREL/TP-6A20-67067, November 2016

ReEDS Results

Capacity (GW)



Energy Generation (TWh)



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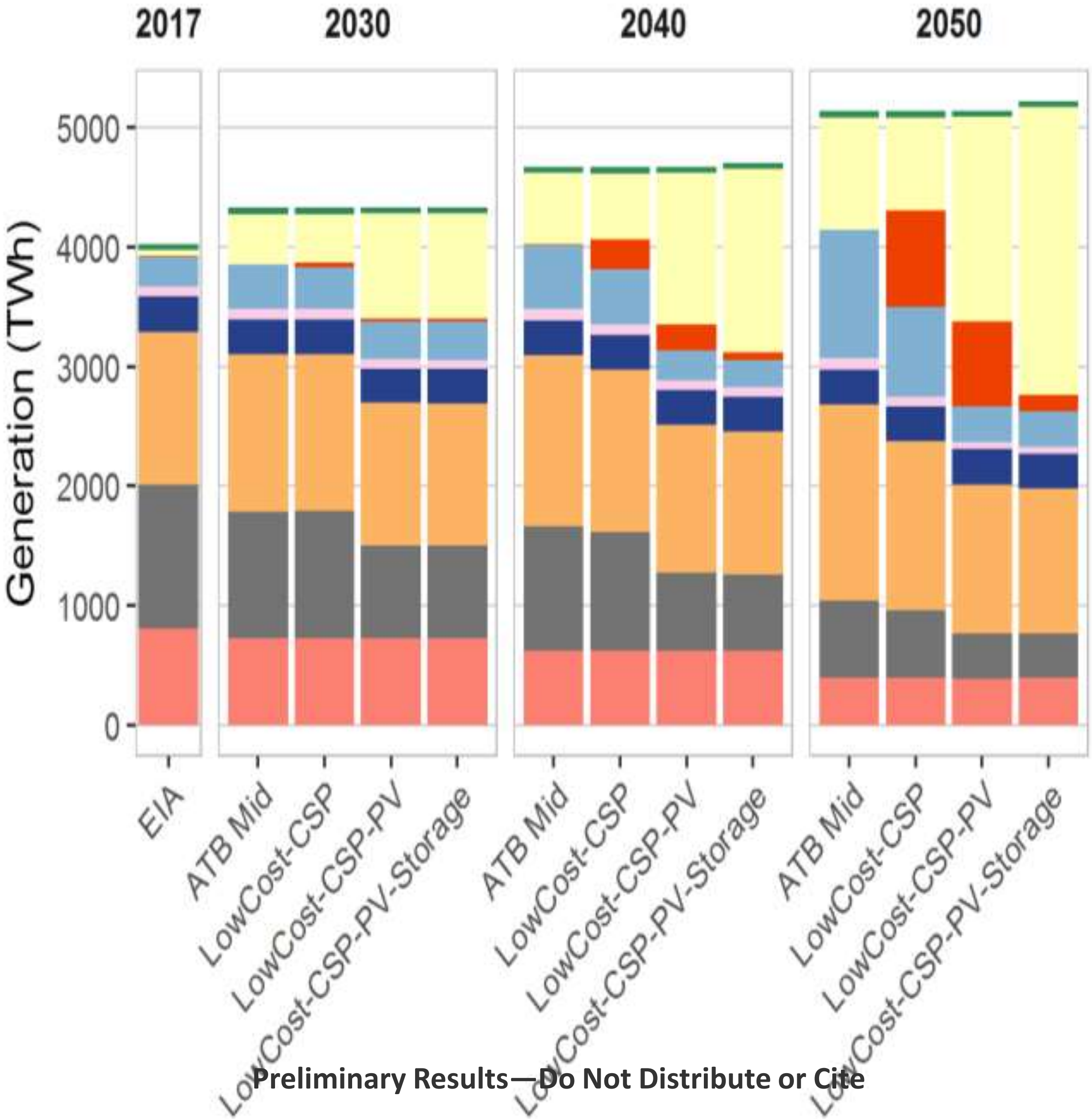

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