U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

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Gen3 CSP Summit

Dr. Avi Shultz, Program Manager

August 25, 2021

Solar Energy Technologies Office (SETO) Overview

MISSION

We accelerate the **advancement** and **deployment of solar technology** in support of an **equitable** transition to a **decarbonized energy system by 2050**, starting with a decarbonized power sector by 2035.

WHAT WE DO

Advance solar technology and drive soft cost reduction to make solar **affordable** and **accessible** for all Americans

Enable solar to **support grid reliability** and pair with storage to provide new options for **community resilience**

Support **job growth**, **manufacturing**, and the **circular economy** in a wide range of applications

Roadmap to Success: 8-10 Year Strategy

Top Priorities

1) **Accelerate solar deployment and associated job growth** by opening new markets, providing workforce training, growing U.S. manufacturing, reducing environmental impacts, and **putting a focus on environmental justice**.

2) Enable inverter-based technologies to provide essential grid services and black start capabilities while demonstrating the **reliable, resilient and secure operation of a 100% clean energy grid**.

3) **Reduce hardware and soft costs** of solar electricity **for all Americans** to enable an affordable carbon-free power sector by 2035.

4) **Support a decarbonized industrial sector** with advanced concentrating solar-thermal technologies and develop affordable renewable fuels produced by solar energy.

Key Goals by 2030

Acceleration

- Enable 5x faster deployment (60 GW_{AC}/yr)
- 65% of the solar hardware installed in U.S. was made or assembled in U.S.

Reliability & Resiliency

- Demonstrate reliable operation of a grid with 75% inverter-based generation by 2025

Costs

- $0.02/kWh for utility-scale photovoltaics
- $0.05/kWh for concentrating solar power
- 100% of energy consumers can choose solar without increasing energy costs by 2025

Net Zero Emissions Energy Sector

- $0.02/kWh for solar process heat at a range of temperatures by 2025)

Long Duration Storage Earthshot

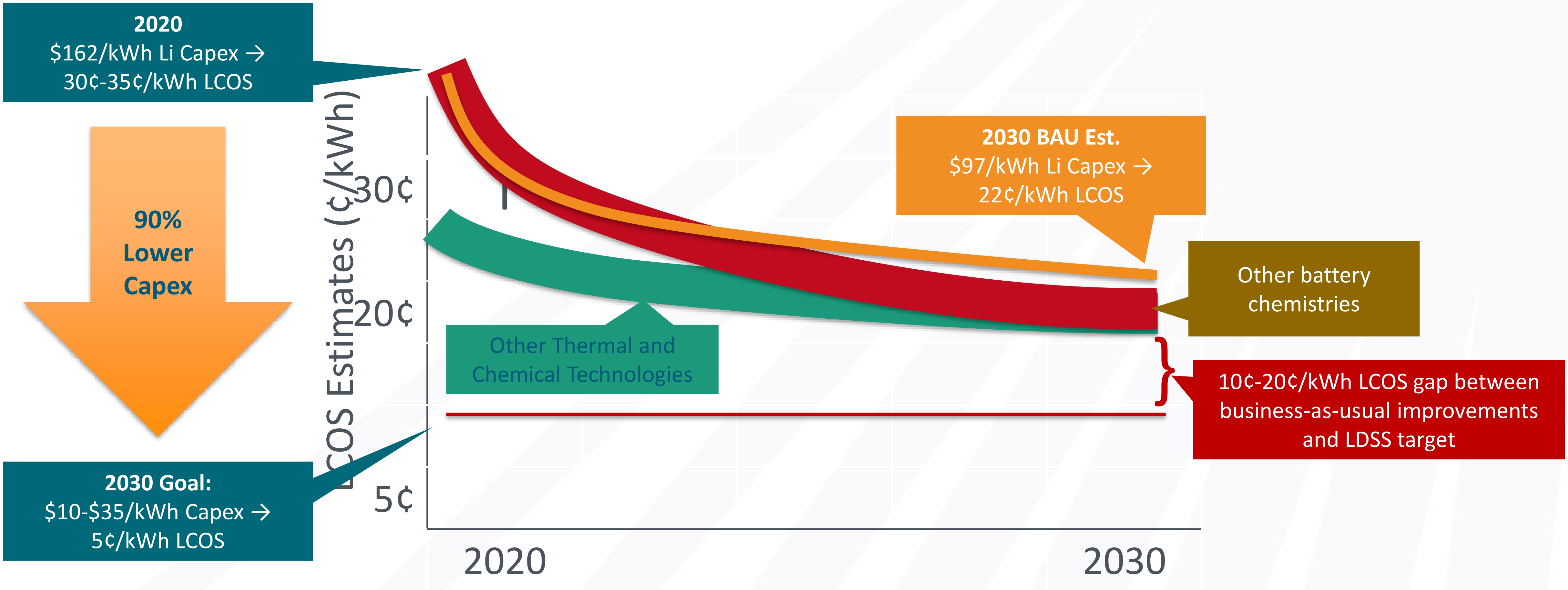
ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Storage

Affordable grid storage for clean power – any time, anywhere

Reduce storage costs by	...in storage systems that deliver	...in
90%	**10+**	**1**
from a 2020 Li-ion baseline...	hours of duration	decade

Significant Storage Cost Decreases Required

Business-as-usual Projections of Storage Price Decreases (10-hour system)



LCOS = Levelized Cost of Storage, or the cost of moving a kilowatt-hour of energy from one time period to another
Li batteries were 99% of grid storage being deployed in 2020: IHS, Grid-Connected Energy Storage Market Tracker, 1 February 2021
2020 and 2030 Battery Costs: DOE-ESGC 2020 Grid Energy Storage Technology Cost and Performance Report

Concentrating Solar-Thermal Power Status and Goals

The goal for SETO's CSP research is to achieve $0.05/kWh for dispatchable CSP with >12 hours of thermal energy storage (TES), with a 50% thermal-to-electric power cycle efficiency at a turbine inlet temperature of > 700 °C

Where we are now:

- Modeled LCOE of $0.098/kWh for a U.S. plant with 14 hours of TES
- 1.7 GW CSP deployed in the U.S., 6.3 GW globally
- 5.1 GW of global deployment is parabolic trough, 1.2 GW is tower
- 45% of global tower capacity and 34% of trough capacity has 6 or more hours of storage

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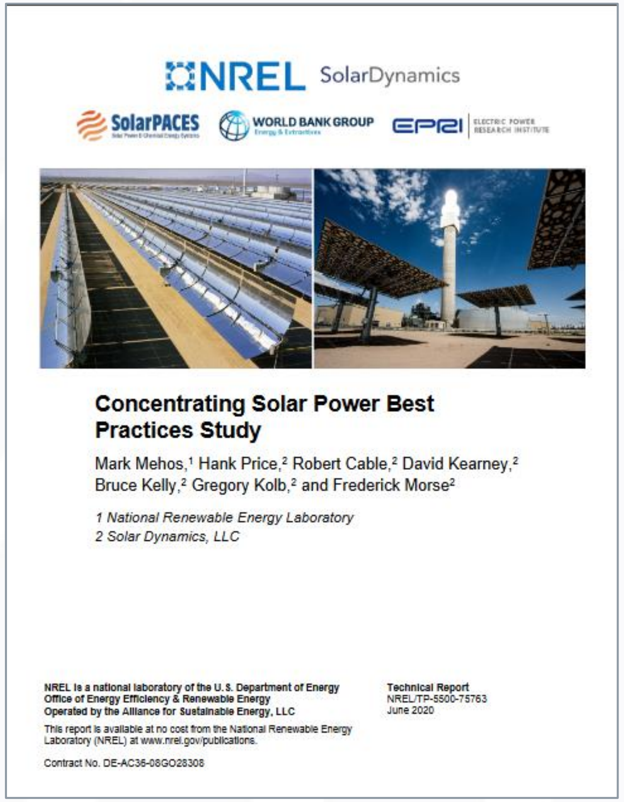
Priority R&D Topics:

- Designing and piloting 'Gen3 CSP' high-temperature (> 700 °C) thermal transport systems
- Lowering the installed cost of highly autonomous heliostats
- Enhancing the performance and reliability of CSP plants
- Developing solar thermal systems and components for solar-driven industrial processes


NREL SolarDynamics

SolarPACES WORLD BANK GROUP EPRI

Concentrating Solar Power Best Practices Study

Mark Mehos,[1] Hank Price,[2] Robert Cable,[2] David Kearney,[2] Bruce Kelly,[2] Gregory Kolb,[2] and Frederick Morse[2]

1 National Renewable Energy Laboratory
2 Solar Dynamics, LLC

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

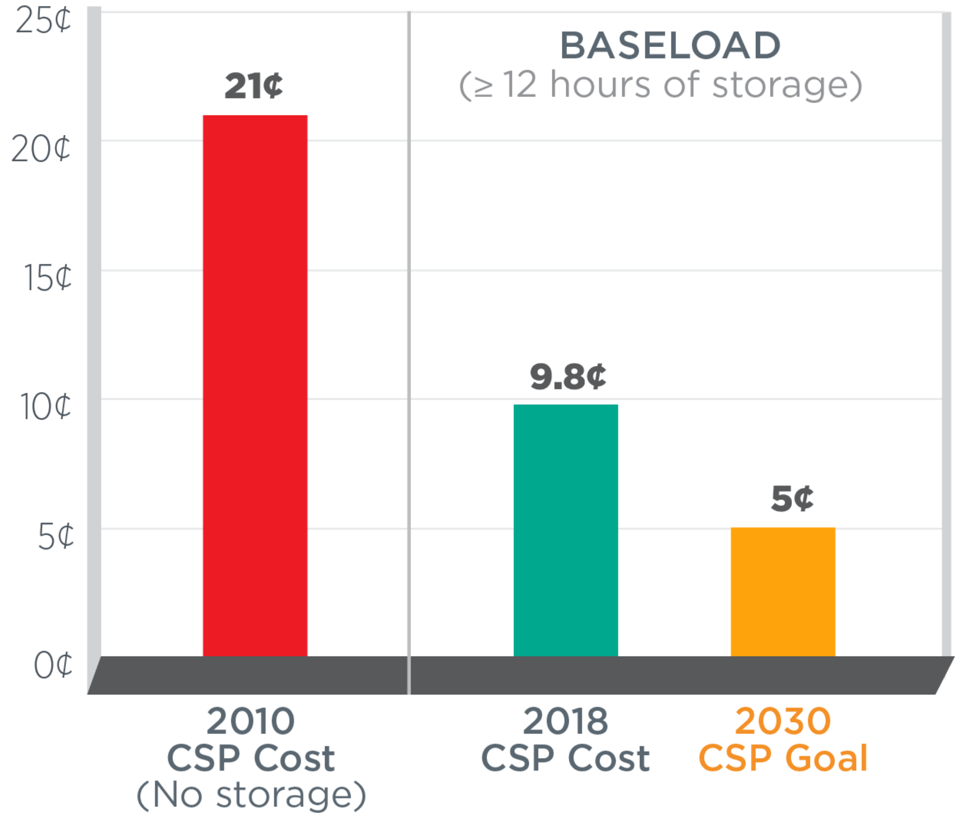
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

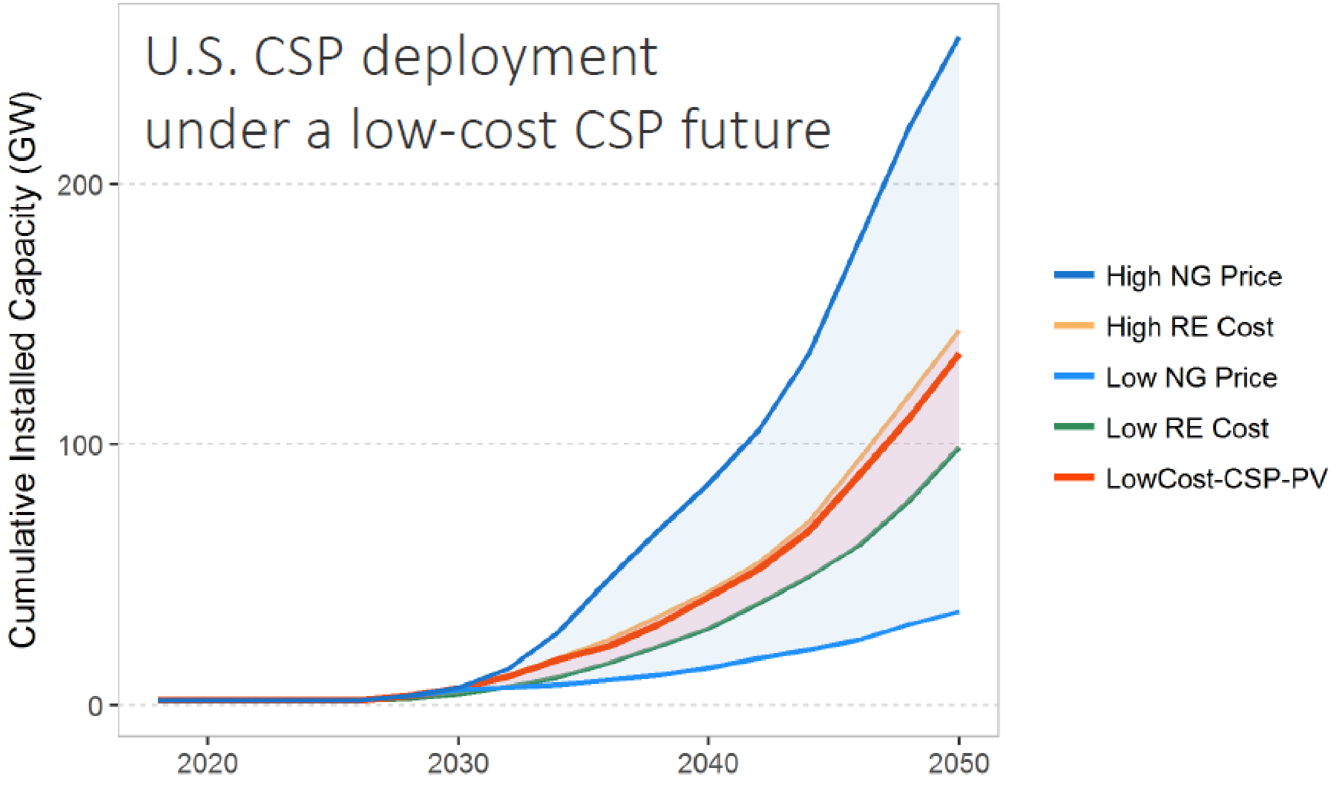
Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-75763
June 2020

Progress and Goals: 2030 LCOE Goals

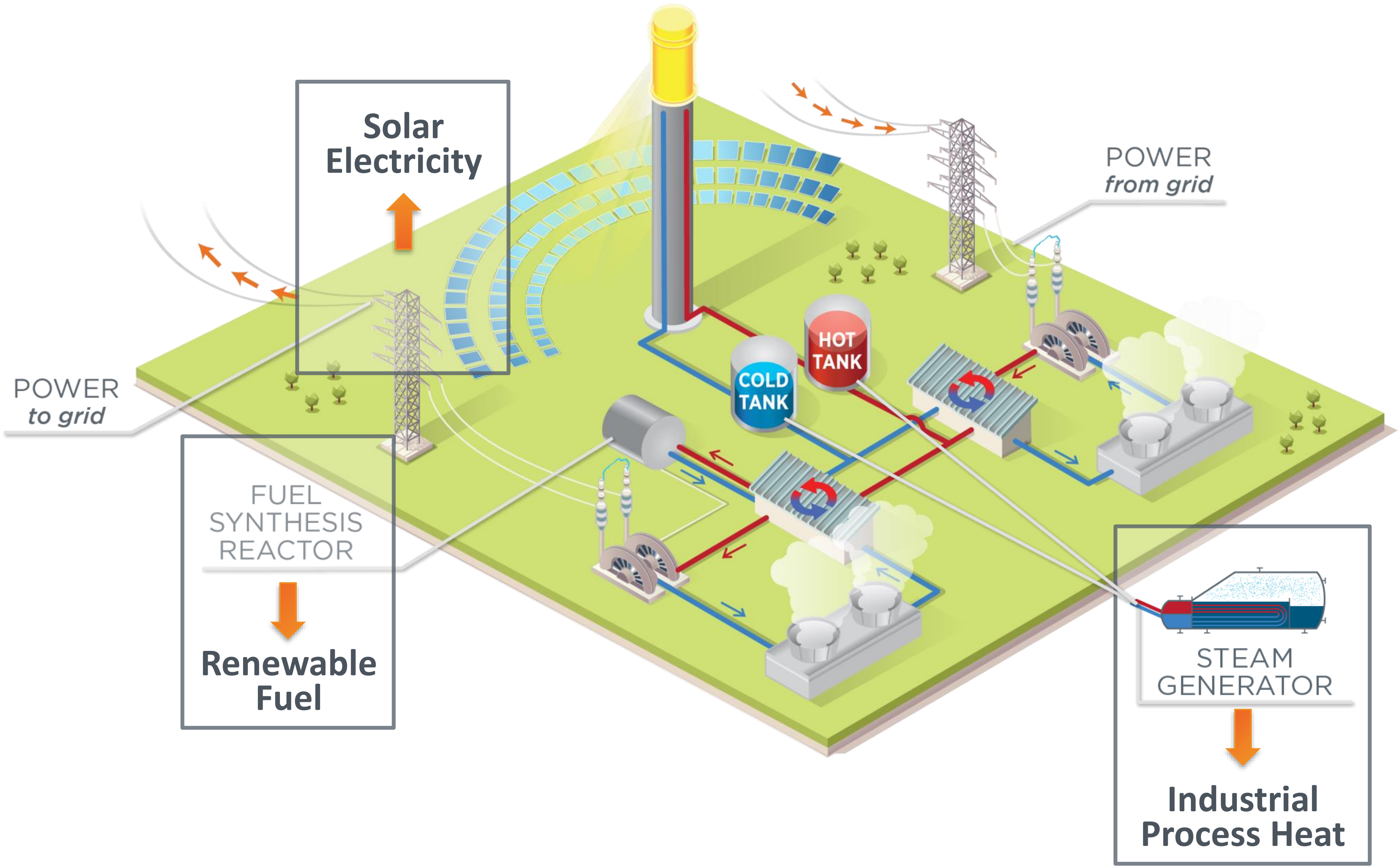
The office's 2030 cost targets for CSP baseload (≥12 hours of storage) plants will help make CSP competitive with other dispatchable generators.





*Levelized cost of energy (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010-18.

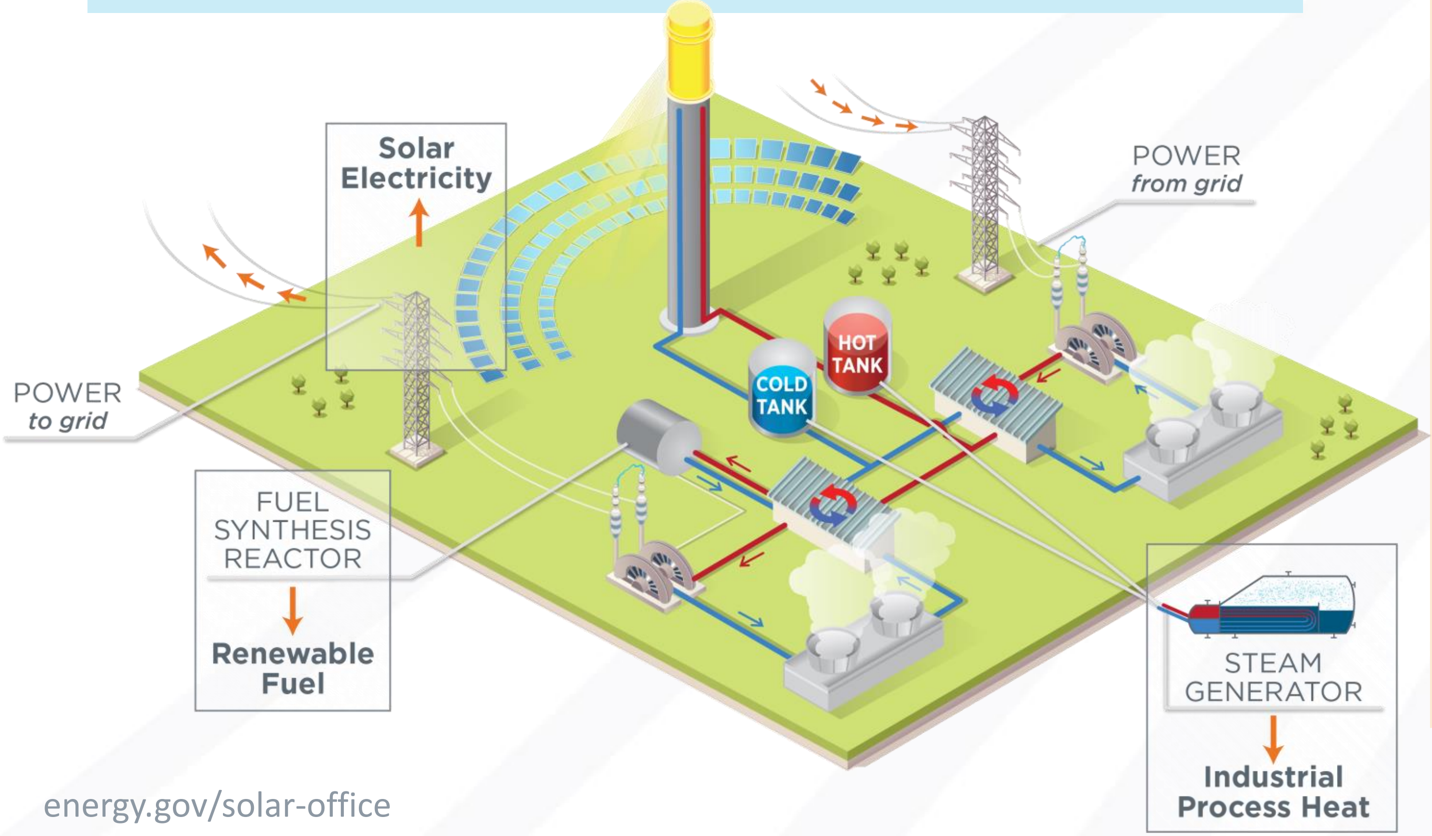
Applications of Solar-Thermal Energy



Solar Thermal for Decarbonization of Industrial Process Heat

Thermally-Driven Industrial Processes:

- Desalination
- Enhanced Oil Recovery
- Agriculture and Food Processing
- Fuel and Chemicals Production
- Mining and Metals Processing



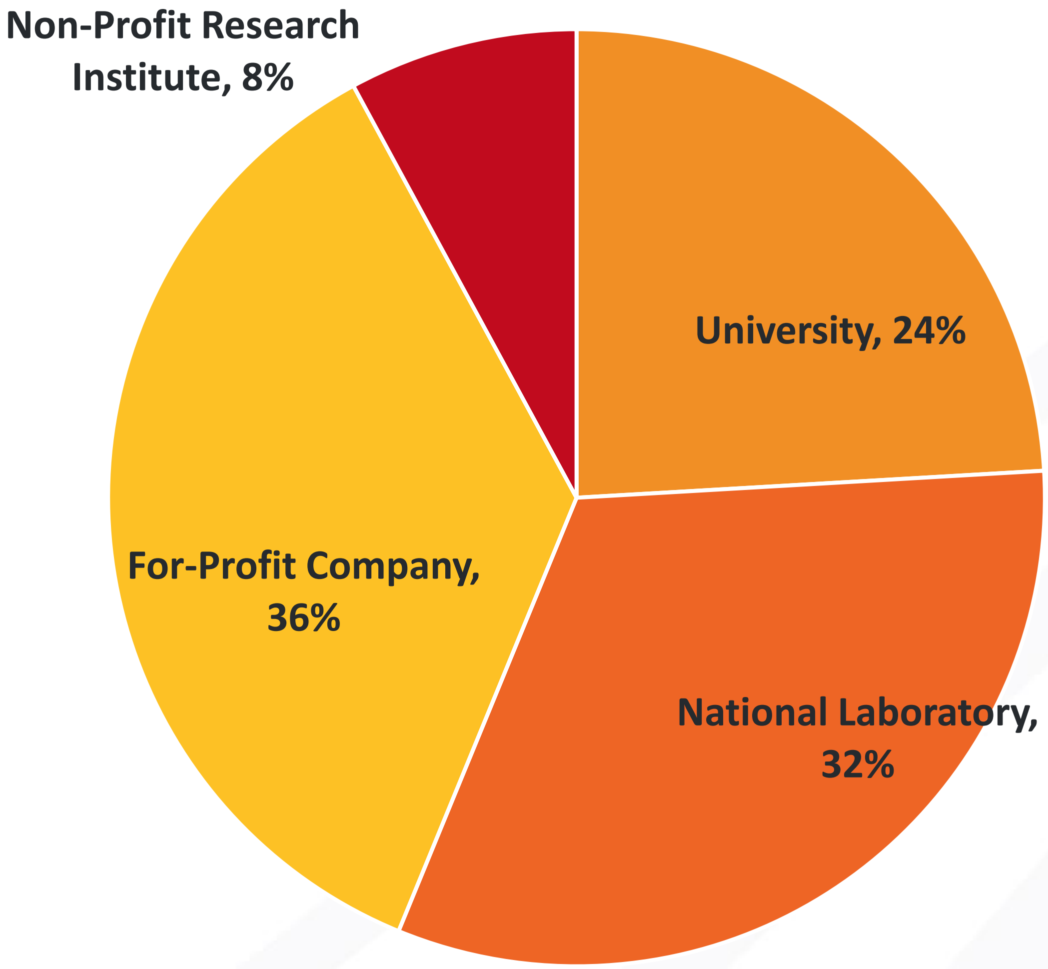
Priority Research Areas:

- Reduce the levelized cost of heat, **with thermal energy storage**, in temperature ranges of high priority to industrial processes
- Improve the **thermal efficiency** of solar-thermal-coupled processes
- Develop long-duration, thermochemical storage of solar energy (i.e. **solar fuels** and chemical commodities)

SETO Goals by 2025:

- Define system concepts and key components for solar process heat for carbon-emissions-intensive, high-heat-demand industries
- Define system concepts and key components for producing fuels from CSP

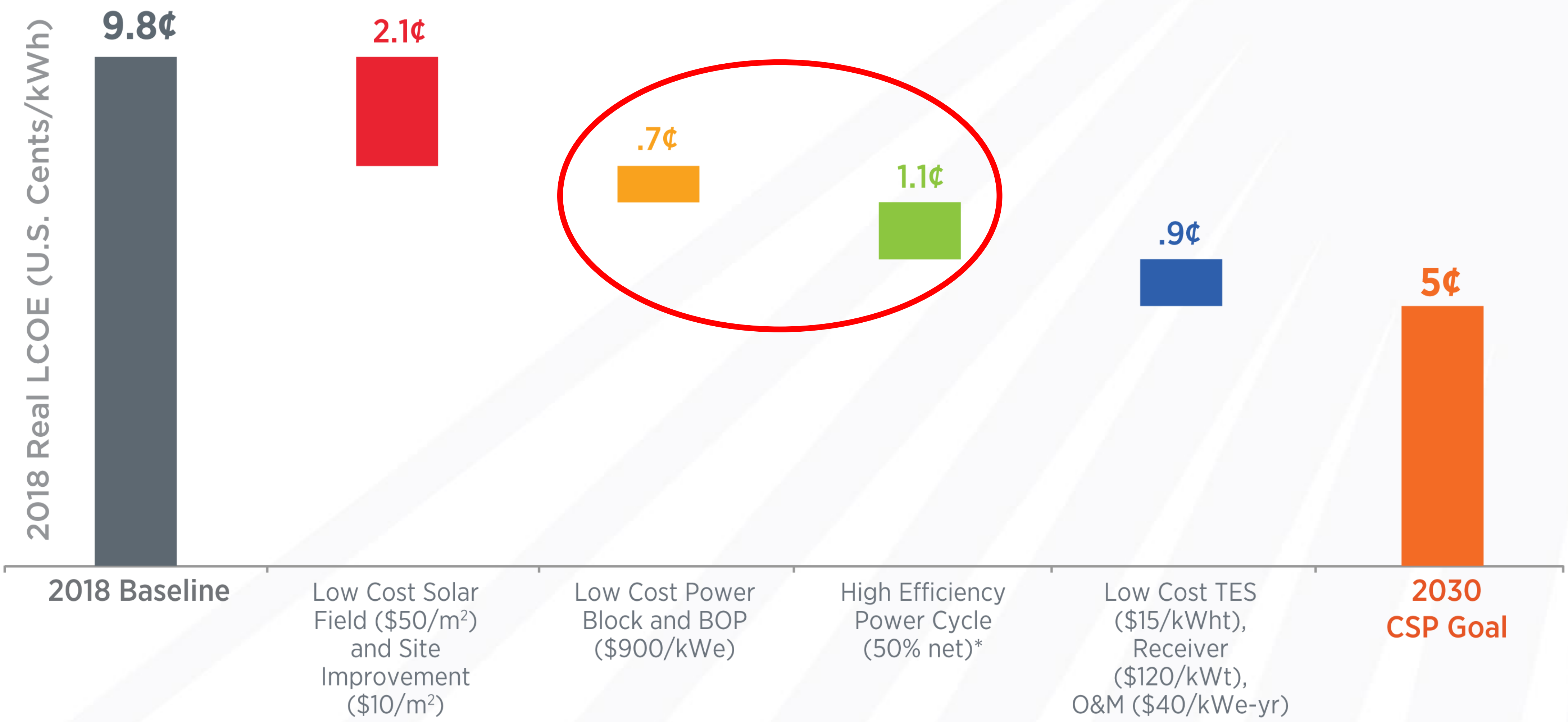
CSP Funding Portfolio



~$185M over ~100 Active Projects

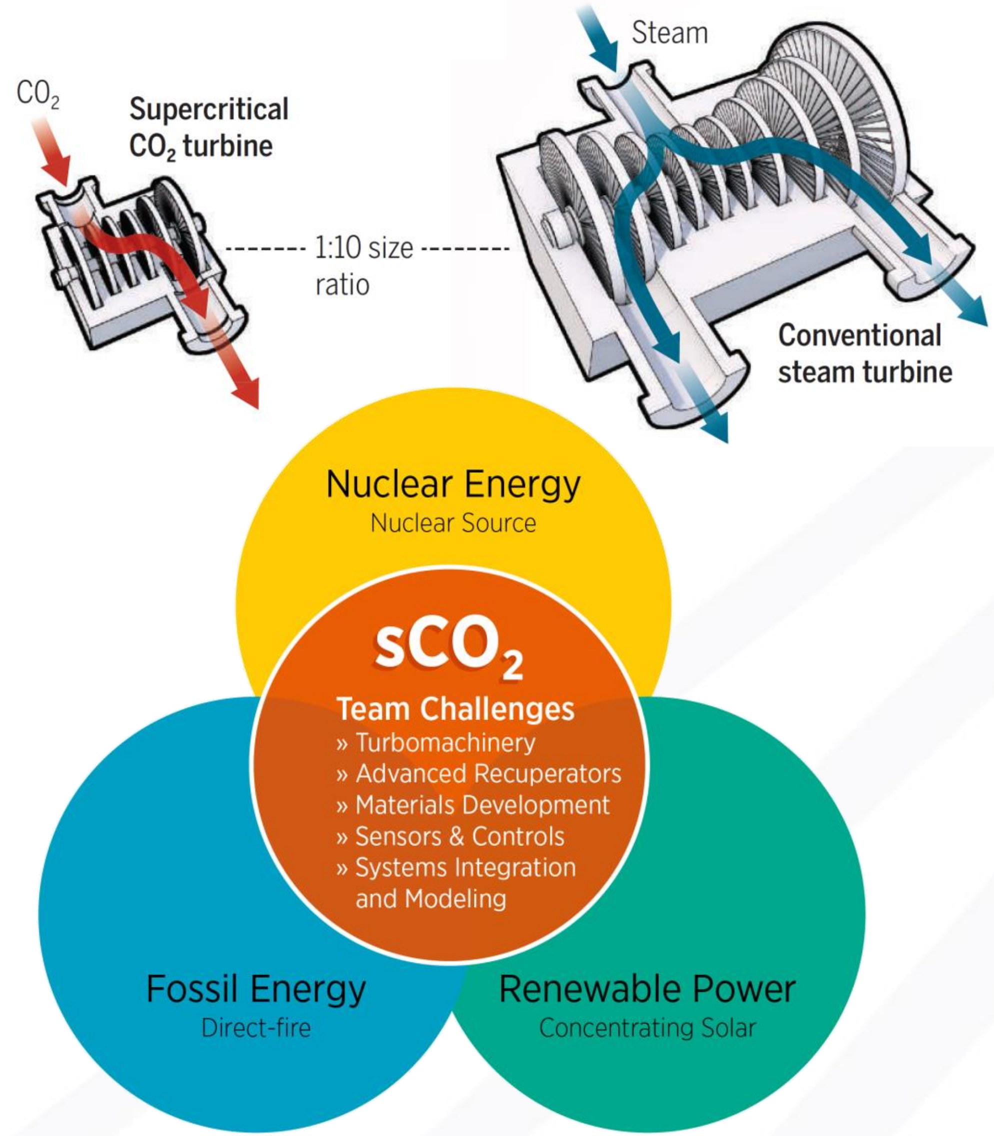
For full research portfolio, visit:
energy.gov/eere/solar/concentrating-solar-power

A Pathway to 5 Cents per KWh for Baseload CSP



*Assumes a gross to net conversion factor of 0.9

Next Generation CSP will Leverage Next Generation Power Cycles



Advantages of the sCO_2 Brayton Cycle:

- Higher Efficiency (50% at ~720 °C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- **Scalability (< 100 MW) with high efficiency**
- Operational Simplicity

Ongoing Research Focus

- Improvements in Expander Design – particularly dry gas seal performance
- Improvements in compressor efficiency and reduction in compression power – especially near dome
- Improvements in Manufacturing
  - Casting or novel manufacturing processes for casing
  - 3D printing or other Novel manufacturing for blades, rotor and bearings
- Integration of compressor and expander into one single casing, drive train; elimination of seals

Integrated Thermal Energy STorage and Brayton Cycle Equipment Demonstration **(Integrated TESTBED)**

Heliogen

Turbomachinery OEM

GE Research

Barber Nichols

Thermal Storage OEM

SIEMENS Gamesa RENEWABLE ENERGY

EPC Partner

PARSONS

R&D Institutions

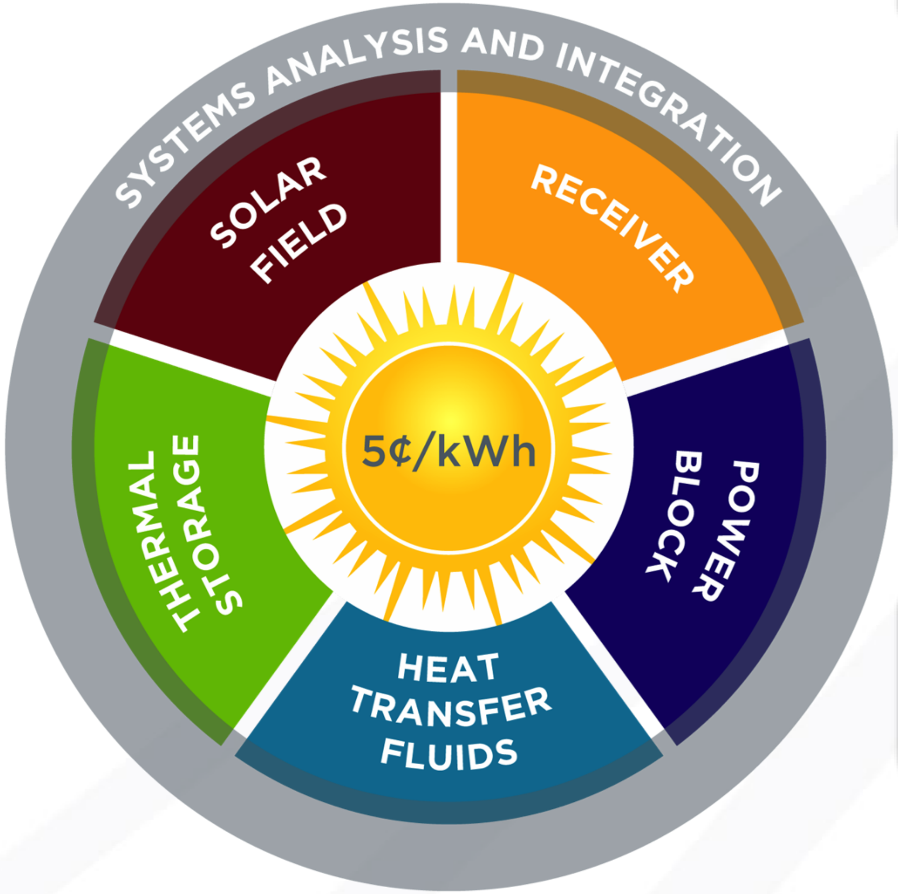
Sandia National Laboratories

SwRI SOUTHWEST RESEARCH INSTITUTE

- Integrated demonstration of a sCO_2 cycle power block heated by **thermal energy storage** at **5 MWe** scale
- Provide **operational experience of the sCO_2 Brayton cycle** for utilities, operators, and developers.
- Public-private partnership cost-shared with **$39 million DOE funding** and **>$31 million private investment**


Gen3CSP
Bringing together the people and the pieces for an
INTEGRATED CSP SYSTEM

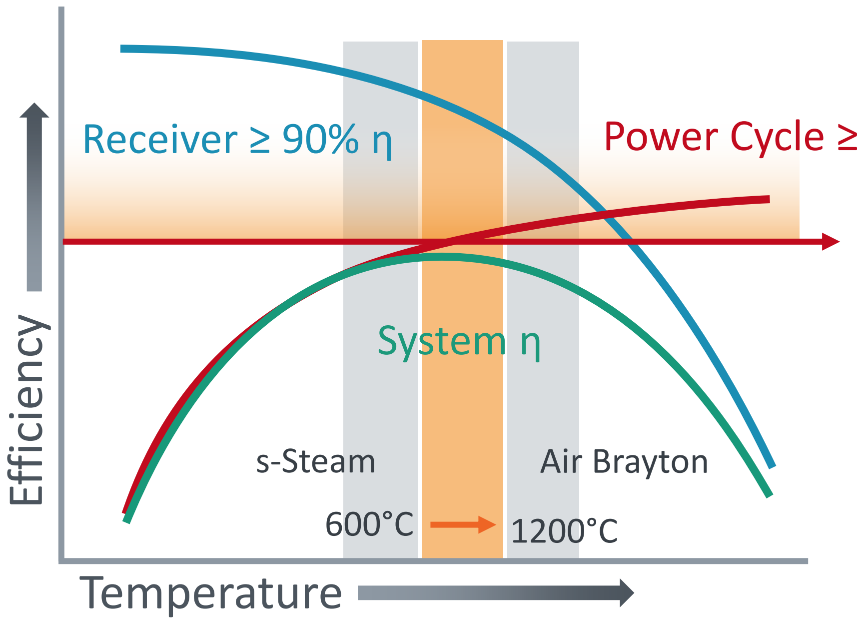
Three waves of Gen3 relevant funding



Competitive Programs

$62M	Gen3CSP Systems (2017)
$15M	Solar Desalination (2017)
$9M	COLLECTS (2016)
$32M	CSP: APOLLO (2015)
$29M	CSP SuNLaMP (2015)
$1.4M	SolarMat II (2014)
$10M	CSP: ELEMENTS (2014)
$1.1M	SunShot Incubator (Recurring)
$4M	PREDICTS (2013)
$2M	SolarMat (2013)
$10M	CSP-HIBRED (2013)
$27M	National Lab R&D (2012)
$10M	SunShot MURI (2012)
$56M	CSP SunShot R&D (2012)
$0.5M	BRIDGE (2012)
$62M	CSP Baseload (2010)
$30M	ARRA (2009)
$35M	Thermal Storage (2008)
$25M	CSP R&D (2007)

Generation 3 CSP Technology



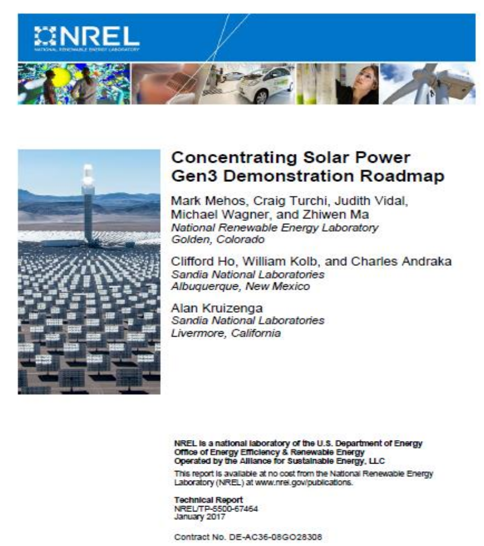
Gen 3 CSP >700 °C

INNOVATION

SOLAR FIELD ASSUMPTIONS	RECEIVER / TOWER	THERMAL ENERGY STORAGE	PRIMARY HEAT EXCHANGER	POWER CYCLE ASSUMPTIONS
\$75/m2	**\$150/kW$_{th}$**	**\$15/kWh$_{th}$**	**\$150/kW$_{th}$**	**\$600 / kW$_e$**
Annual Average Efficiency 50%	Thermal Efficiency ≥ 90%	Energetic Efficiency: >99%	Power Cycle Inlet: >700ºC	Design Point Turbine inlet: 715ºC / 250 bar

Gen3 Pathway Development

- Black and Veatch cost study for a 10MW power plant using chloride salt or particles for heat transfer media
- Series of workshops developing potential Gen3 pathways with CSP R&D community
- Commissioned NREL/SNL to draft technical report on gaps and status of 700 C + Heat transfer media for integrated test


NREL

Concentrating Solar Power Gen3 Demonstration Roadmap

Mark Mehos, Craig Turchi, Judith Vidal, Michael Wagner, and Zhiwen Ma
National Renewable Energy Laboratory
Golden, Colorado

Clifford Ho, William Kolb, and Charles Andraka
Sandia National Laboratories
Albuquerque, New Mexico

Alan Kruizenga
Sandia National Laboratories
Livermore, California

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Technical Report
NREL/TP-5500-67464
January 2017

Contract No. DE-AC36-08GO28308

Gen3 Pathway Challenges

- High temperature thermal transport systems were immature for the ~10 MW scale
- Small Brayton cycle ΔT has strong effect on TES cost
- High temperature piping going up and down the tower can be a cost breaker
- Significant uncertainty in any high-flux receiver performance, especially with transients

Collector Field

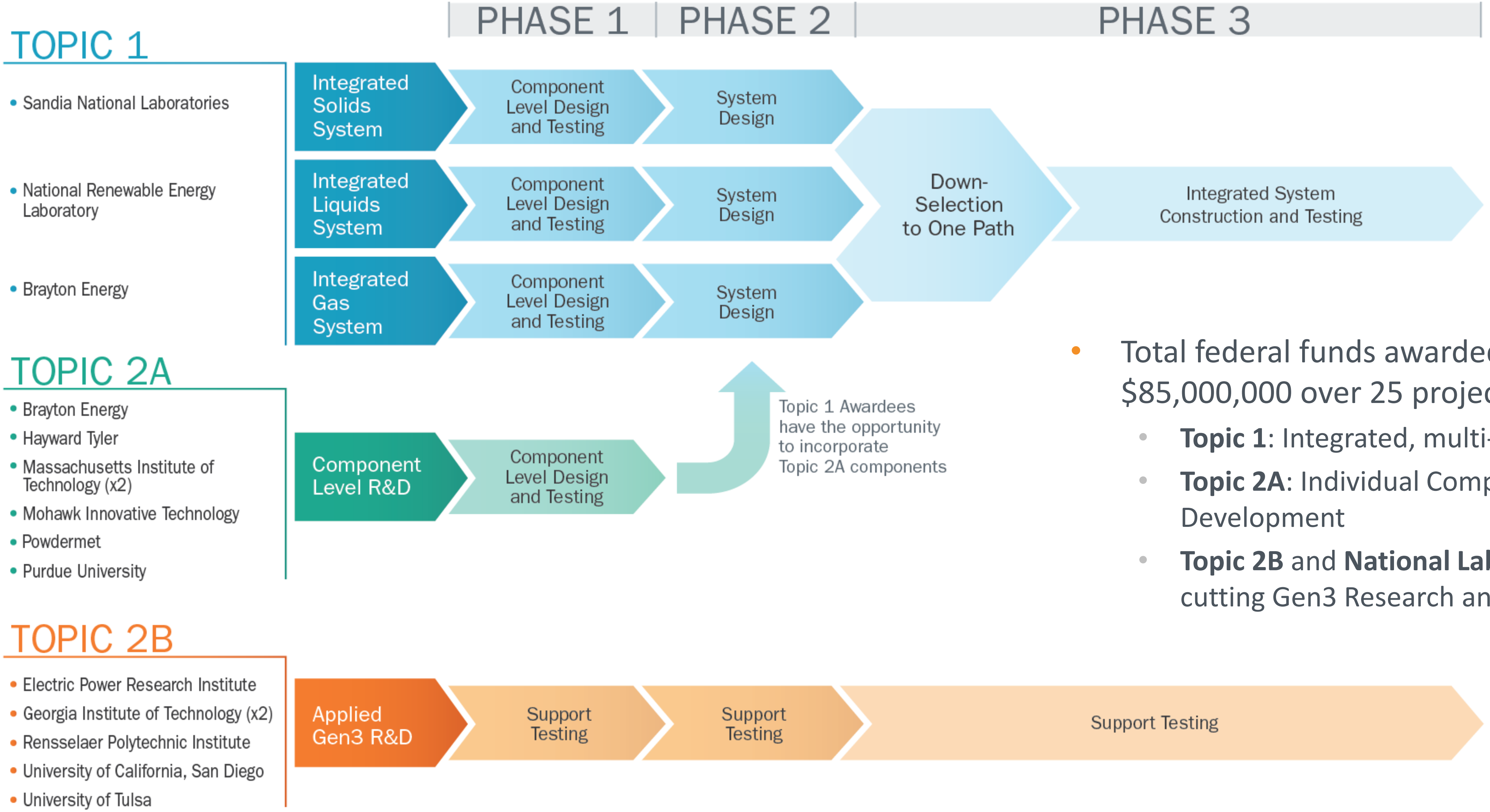
- Cost <$75/m²
- Concentration ratio >50
- Operable in 35-mph winds
- Optical error <3.0 mrad
- 30-year lifetime

	Molten Salt	Falling Particle	Gas Phase
Receiver *Cost < $150/kWth* *Thermal Efficiency > 90%* *Exit Temperature > 720°C* *10,000 cycle lifetime*	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Most challenging to achieve high thermal efficiency	• High-pressure fatigue challenges • Absorptivity control and thermal loss management
Material & Support *Cost < $1/kg* *Operable range from 250°C to 800°C*	• Potentially chloride or carbonate salt blends; ideal material not determined • Corrosion concerns dominate	• Suitable materials readily exist	• Minimize pressure drop • Corrosion risk retirement
Thermal Storage *Cost < $15/kW$_{th}$* *99% energetic efficiency* *95% exergetic efficiency*	• Direct or indirect storage may be superior	• Particles likely double as efficient sensible thermal storage	• Indirect storage required • Cost includes fluid to storage thermal exchange
HTF to sCO_2 Heat Exchanger	• Challenging to simultaneously handle corrosive attack and high-pressure working fluid	• Possibly greatest challenge • Cost and efficiency concerns dominate	• Not applicable

Supercritical CO_2 Brayton Cycle

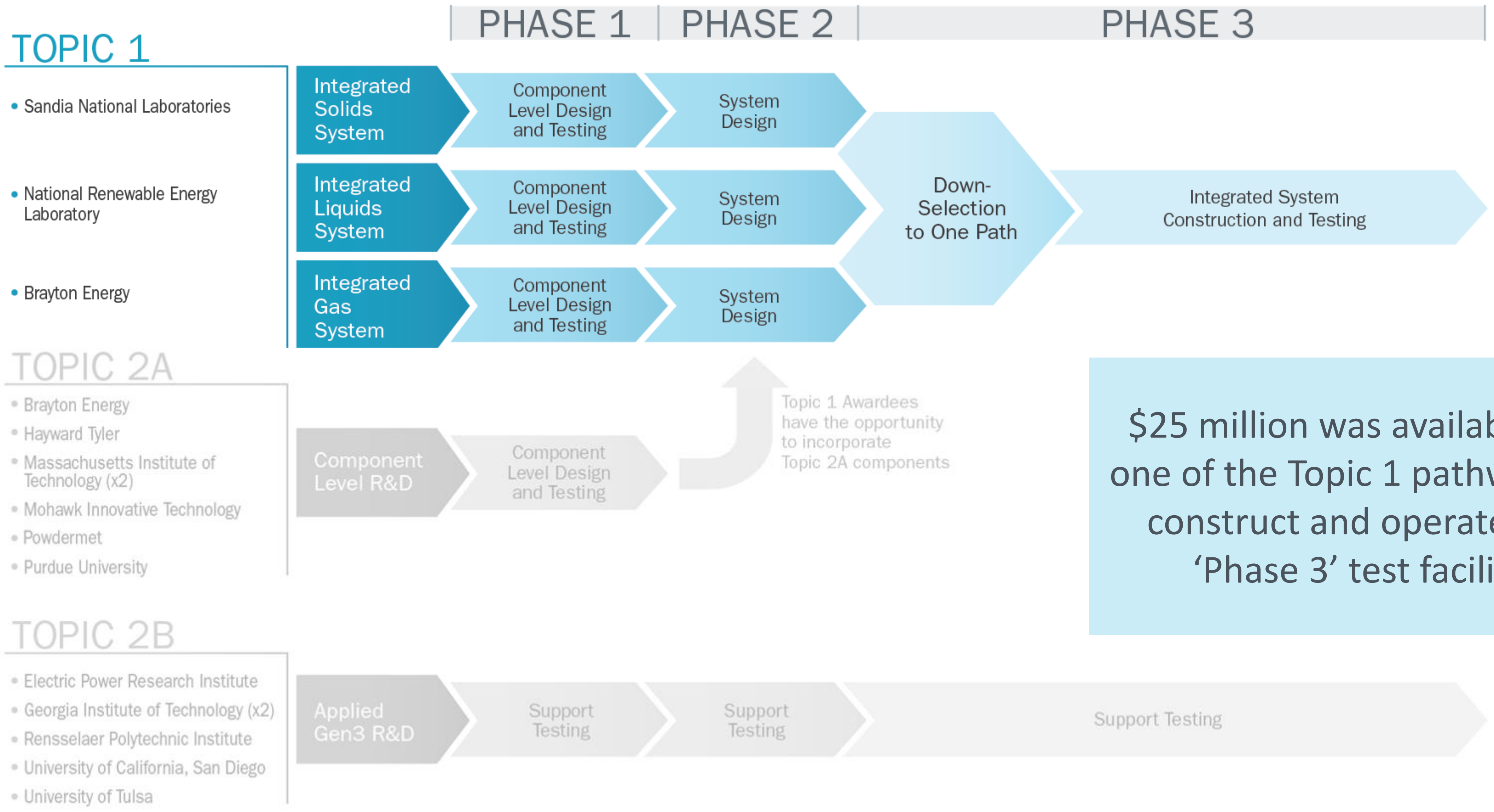
- Net thermal-to-electric efficiency > 50%
- Power-cycle system cost < $900/kW$_e$
- Dry-cooled heat sink at 40° C ambient
- Turbine inlet temperature ≥ 700°C

Gen3 CSP: Solar Thermal Transport Systems > 700 °C



- Total federal funds awarded in 2018: $85,000,000 over 25 projects in 3 Topics:
  - **Topic 1**: Integrated, multi-MW test facility
  - **Topic 2A**: Individual Component Development
  - **Topic 2B** and **National Lab Support**: Cross-cutting Gen3 Research and Analysis

Gen3 CSP: Solar Thermal Transport Systems > 700 °C

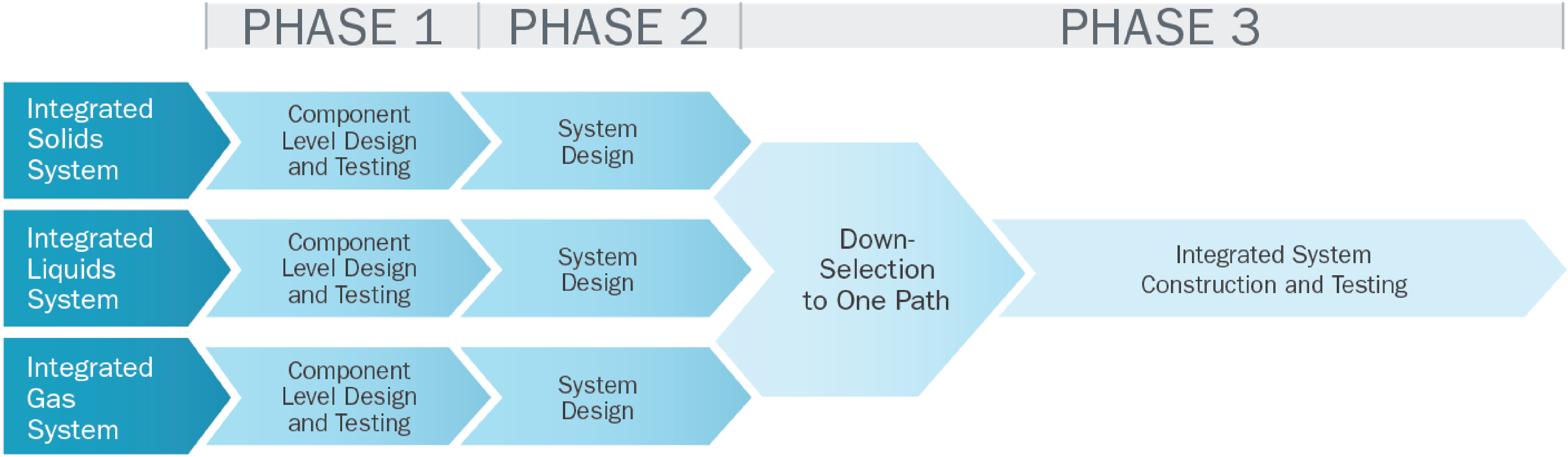


$25 million was available for one of the Topic 1 pathways to construct and operate the 'Phase 3' test facility

Gen3 CSP: Raising the Temperature of Solar Thermal Systems

TOPIC 1

- Sandia National Laboratories
- National Renewable Energy Laboratory
- Brayton Energy



Executive Summaries of Phase 1/2 accomplishments are available at:
https://bit.ly/gen3-summit-2021

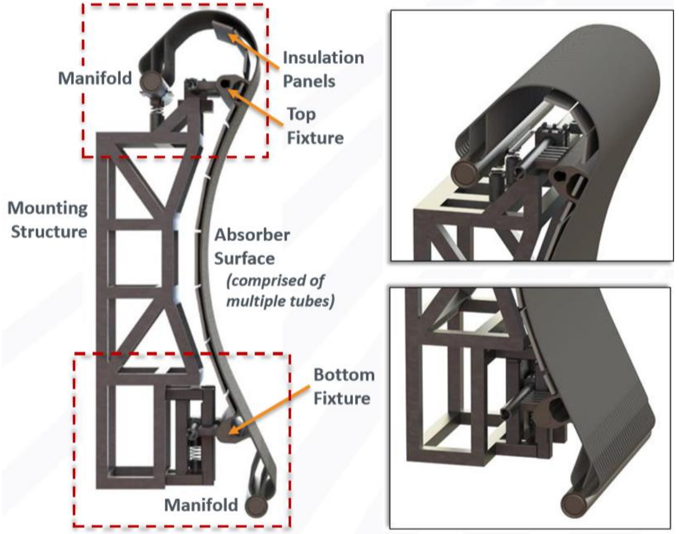
‘Gas’ Gen3 CSP Pathway

TOPIC 1

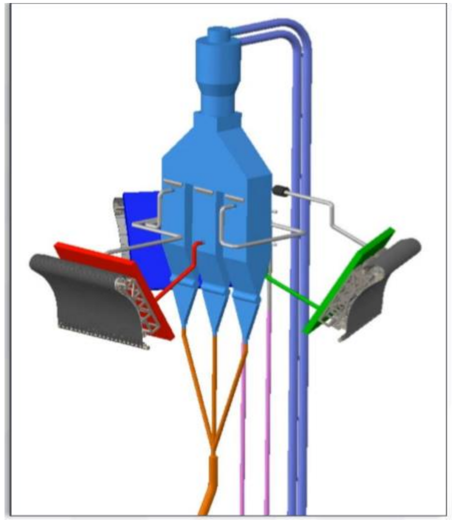
- Brayton Energy

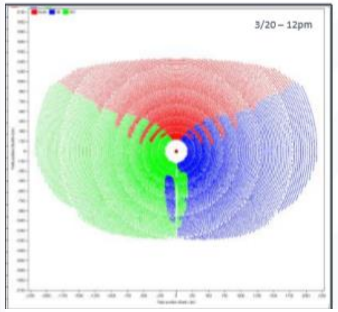
	PHASE 1	PHASE 2	PHASE 3	
Integrated Solids System	Component Level Design and Testing	System Design	Down-Selection to One Path	Integrated System Construction and Testing
Integrated Liquids System	Component Level Design and Testing	System Design		
Integrated Gas System	Component Level Design and Testing	System Design		

Receiver Design and Modelling

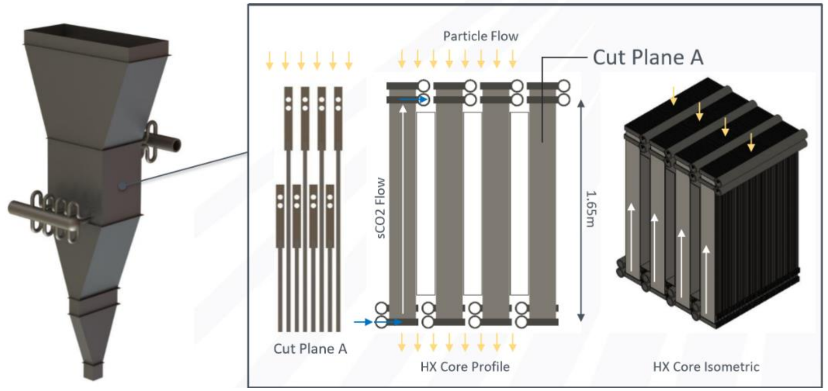


Tower and Solar Field Design

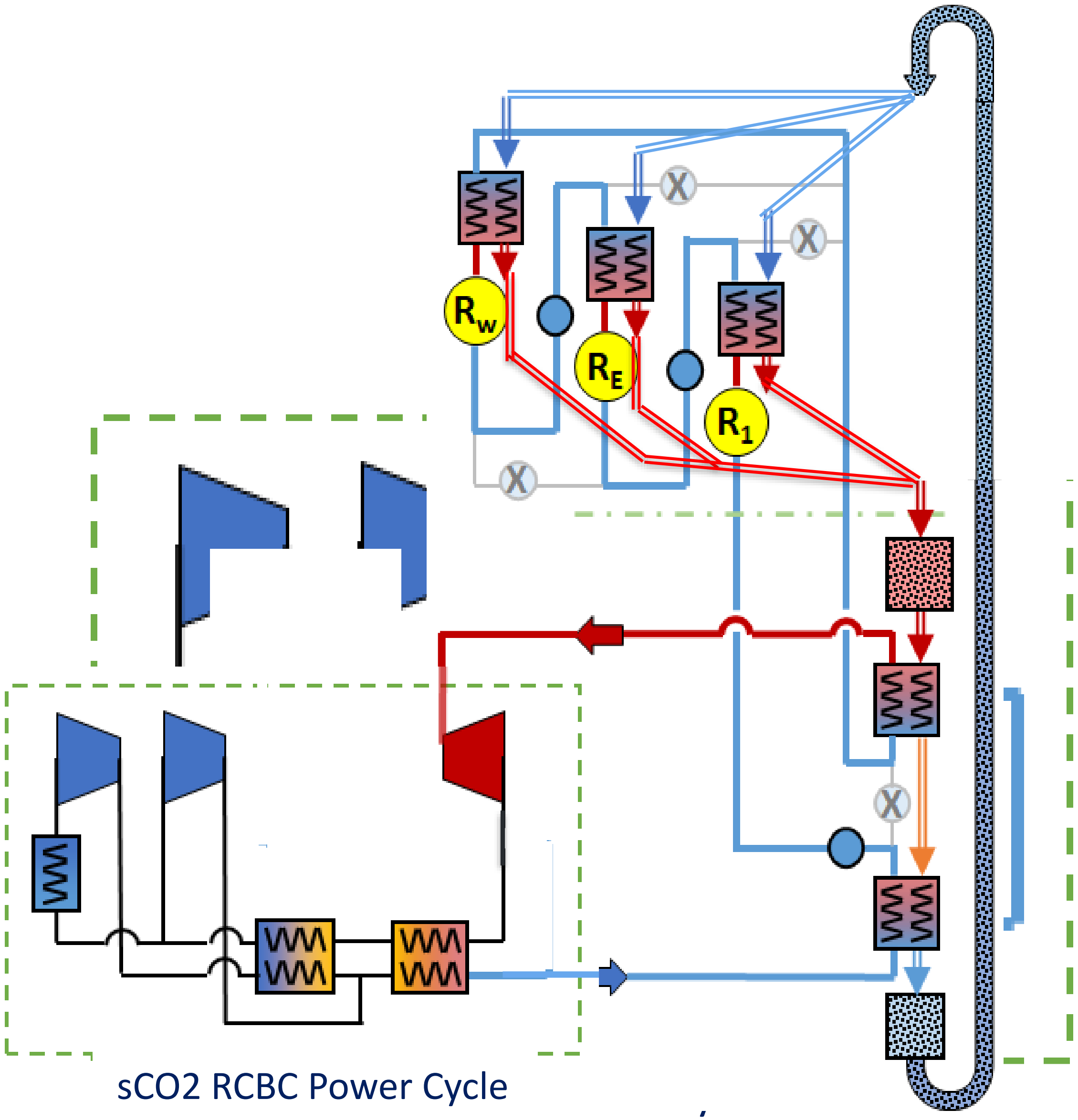




Particle TES and Heat Exchanger



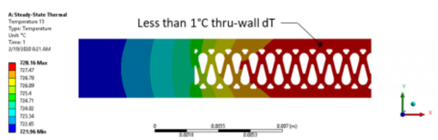
State of the technology – Gas Pathway

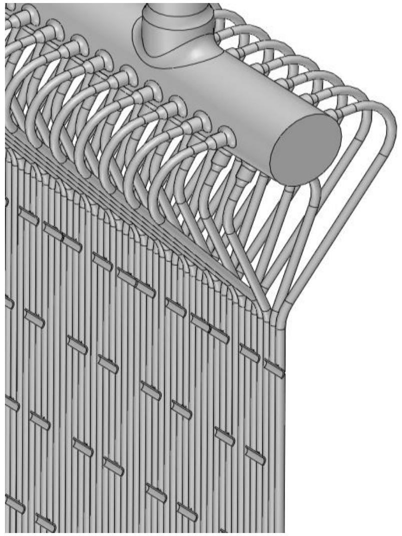


sCO2 RCBC Power Cycle

- Mass flow is dictated by power block
- Heat input is constrained by peak allowable receiver material temp.

Charge TES HX Cross Section at Life Limiting Location





Tubular Receiver Panel Design

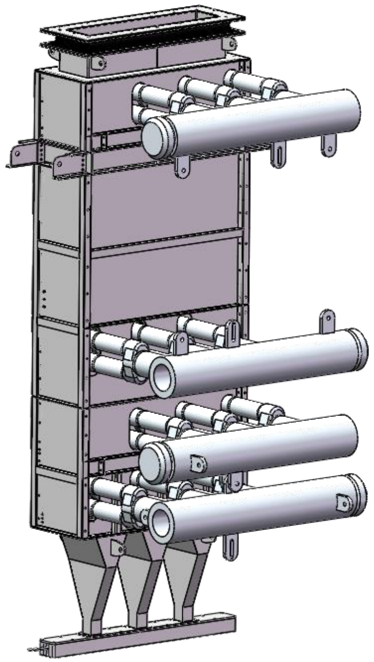
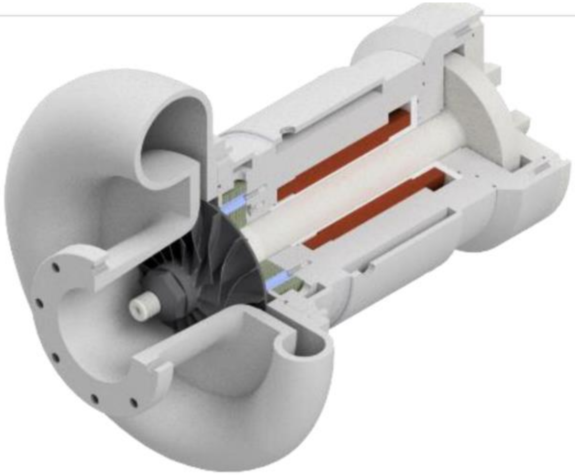


Plate and Plugged Flow Channel Hx

Related Gas Pathway Accomplishments

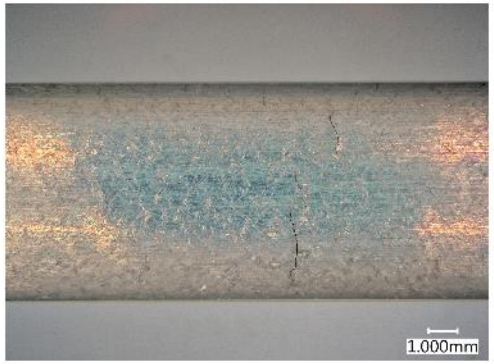
High-Temperature fluid circulator development



Mohawk Innovative Technologies, Inc

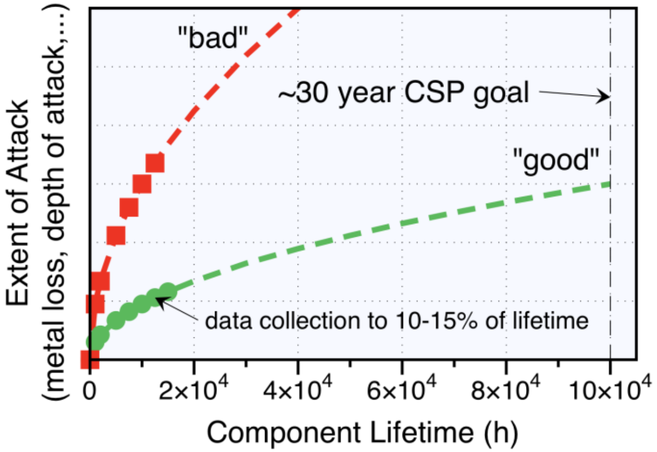
High-temperature alloy development

EPRI - 740H Seam Welded Pipe

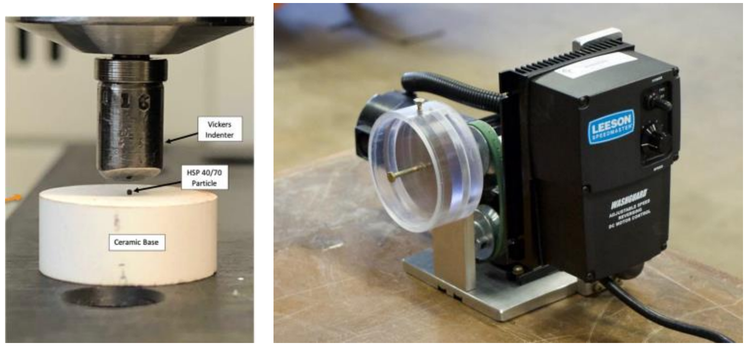


Idaho NL, Argonne – Creep/fatigue characterization and receiver design

Material Metrology and Characterization



Oak Ridge – sCO_2 Corrosion Lifetime Model Development



U. Tulsa – Development of GEN3 Durability Life Models

Liquid Gen3 CSP Pathway

TOPIC 1

- National Renewable Energy Laboratory

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

	PHASE 1	PHASE 2	PHASE 3	
Integrated Solids System	Component Level Design and Testing	System Design	Down-Selection to One Path	
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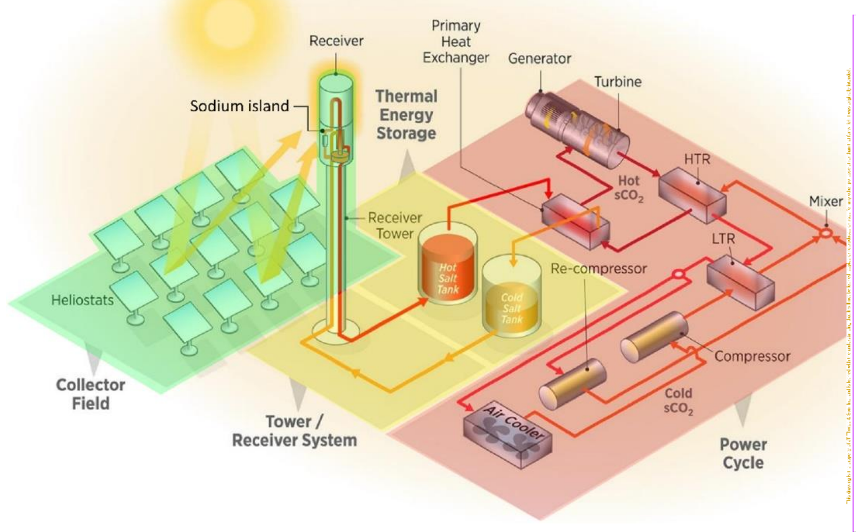
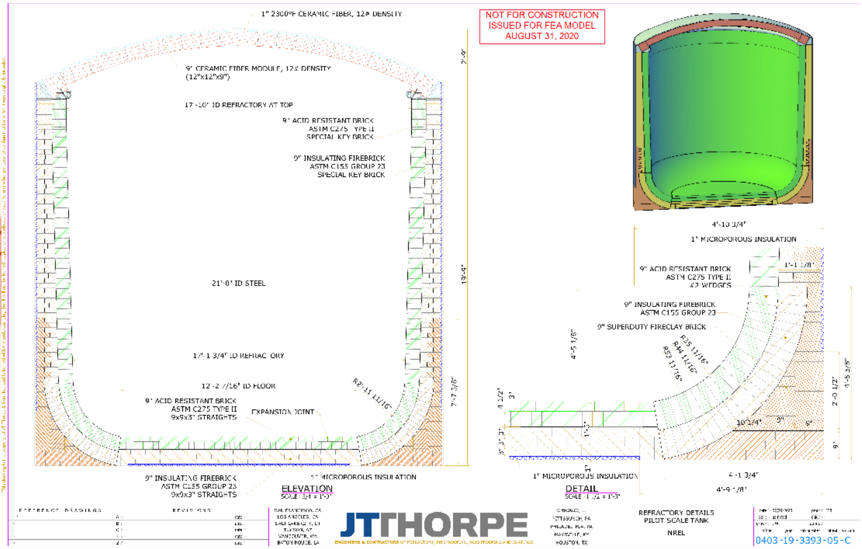
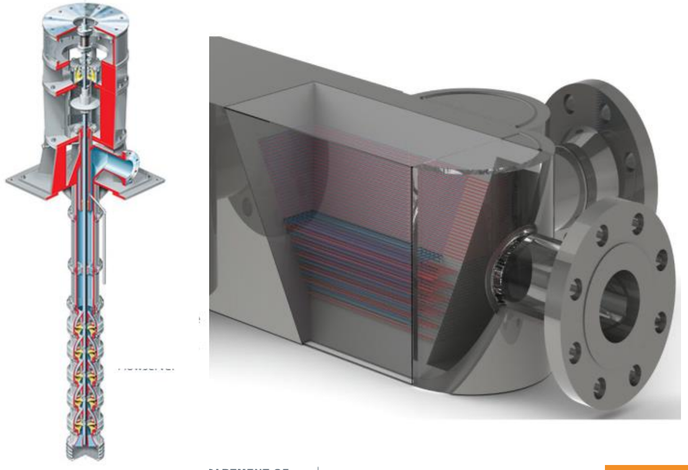
Integrated System Design



Molten Chloride Tank Design



Component Design and Prototyping

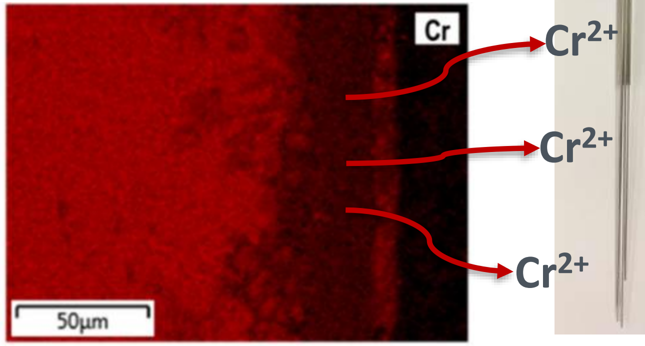


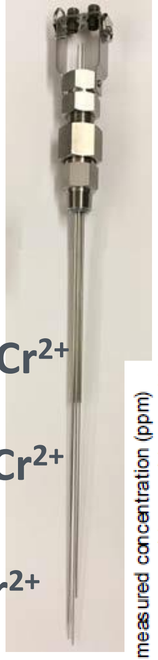
State of the technology – Liquid Pathway

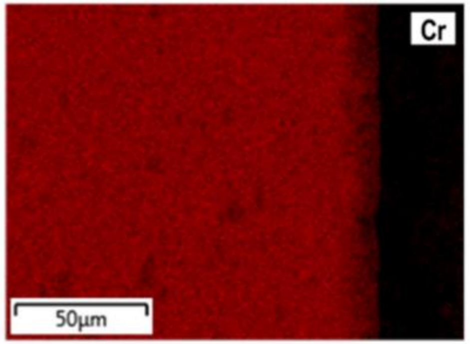
Mass Ratio: 45 $MgCl_2$, 39 KCl, 16 NaCl

The salt is a chemical…
for which you must keep water out.

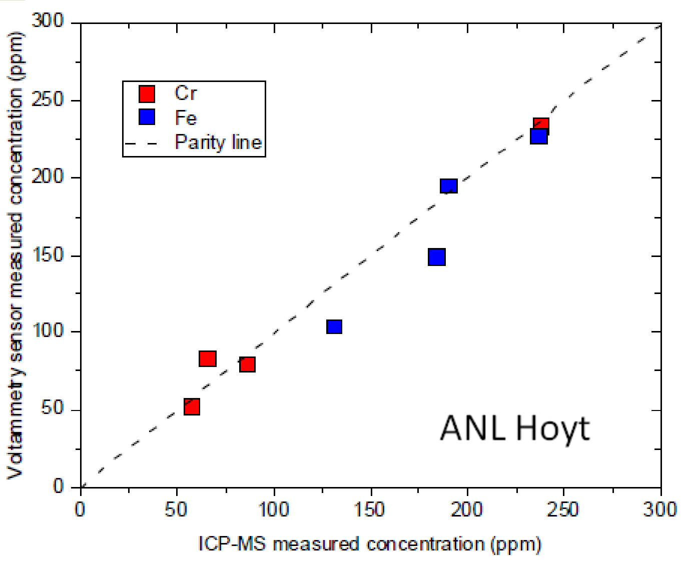
‘Dirty Salt’ esp. H_2O







‘Clean Salt’ – no H_2O



Electrochemical
real-time monitoring
of salt health

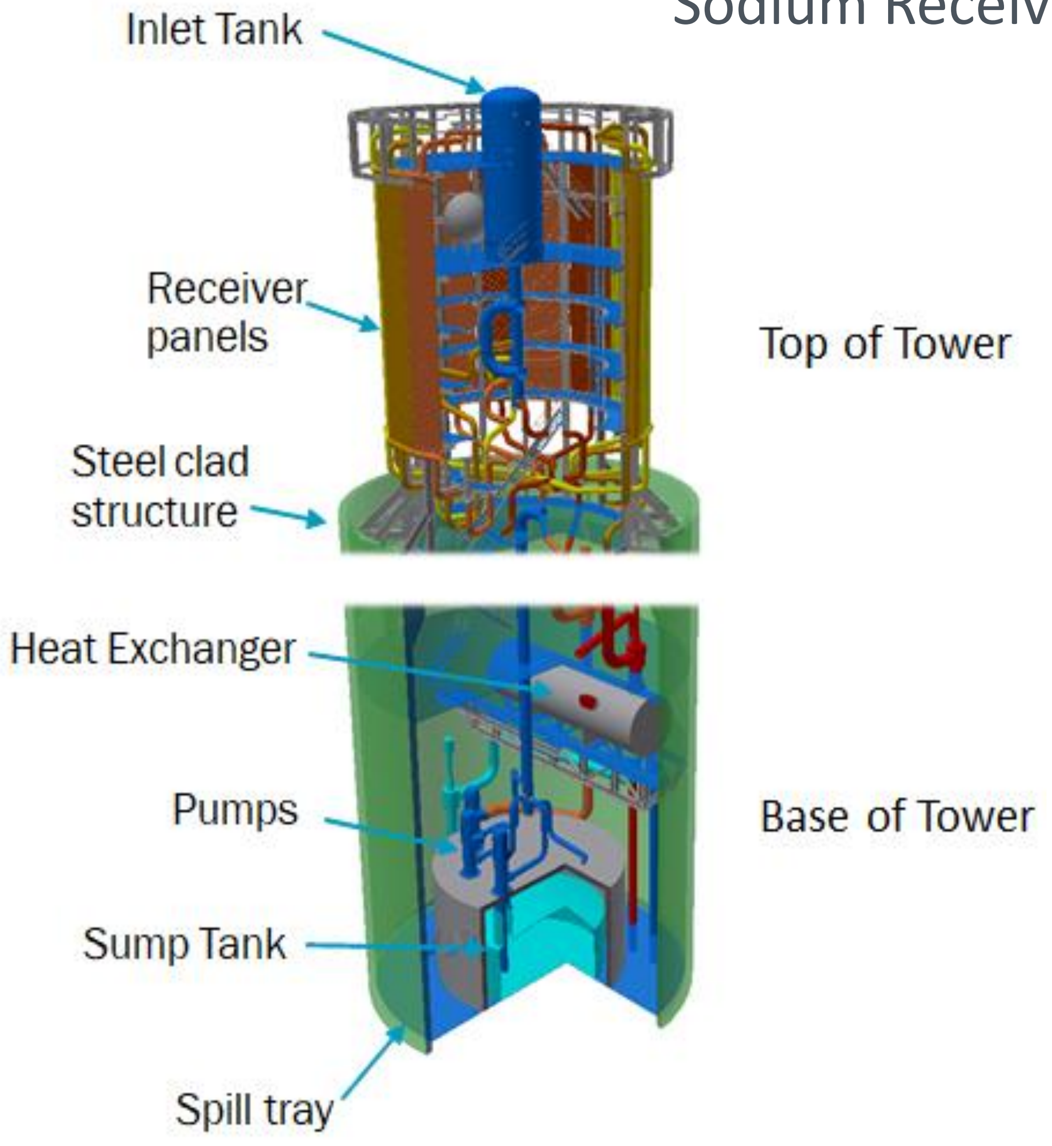
State of the technology – Liquid Pathway

Salt or Sodium in the Receiver?

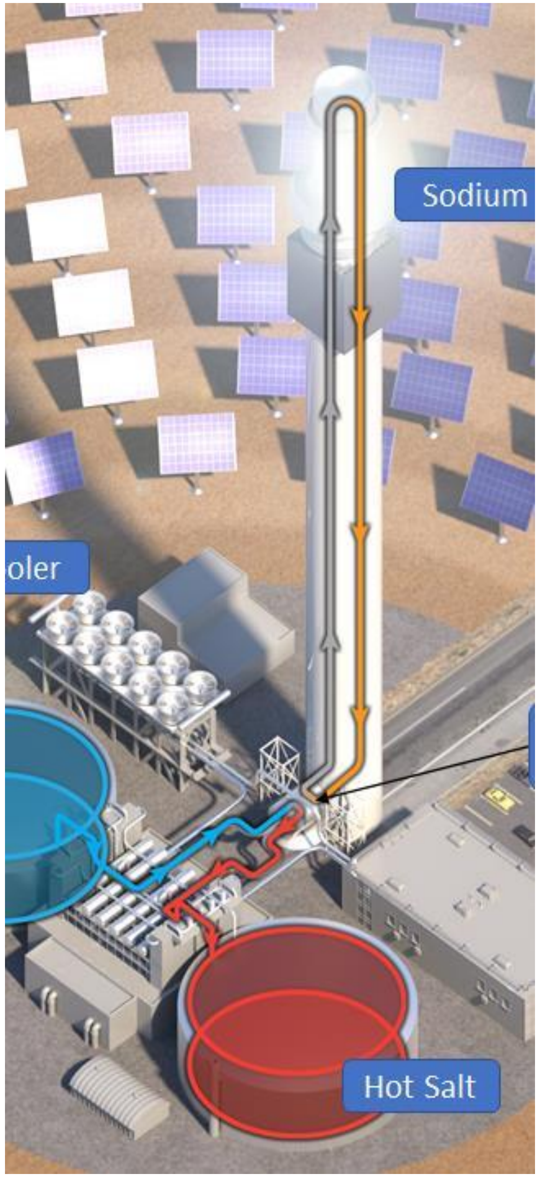
Salt: Lower thermal conductivity and higher freeze point resulted in higher materials-level risks, tighter operating constraints

Sodium: Higher thermal conductivity resulted in lower materials-level risks, more forgiving operating constraints

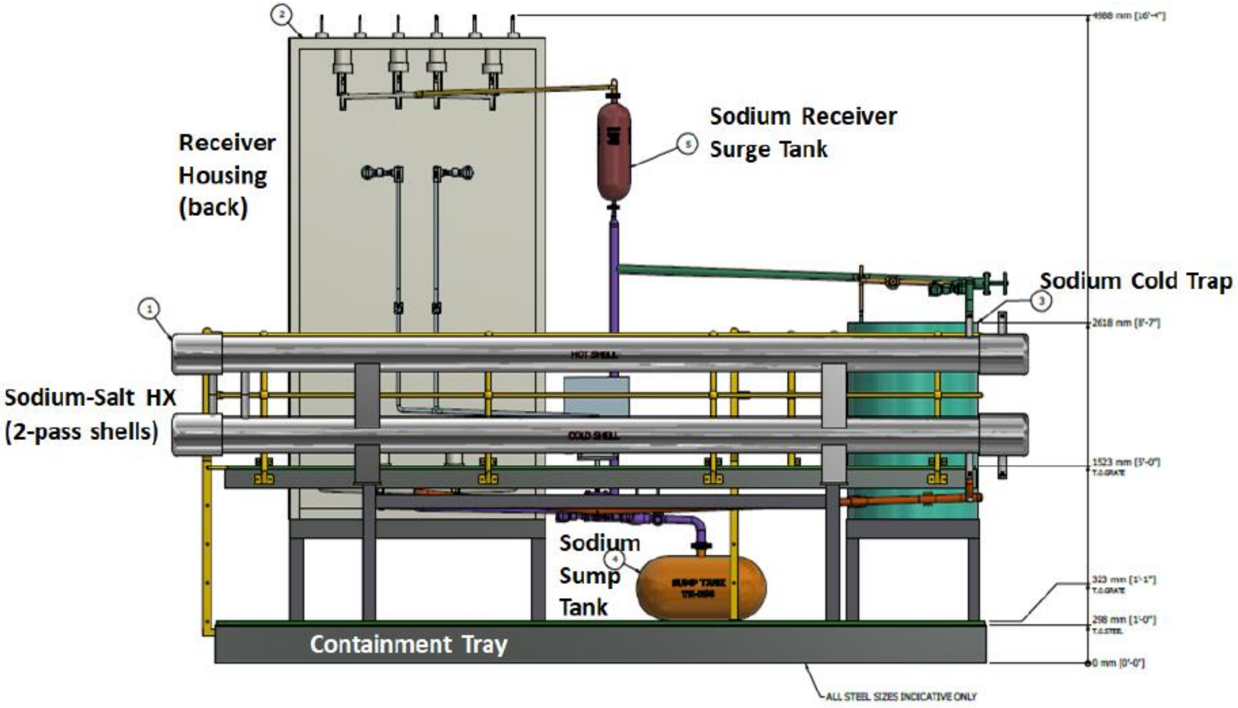
Sodium Receiver



State of the technology – Liquid Pathway



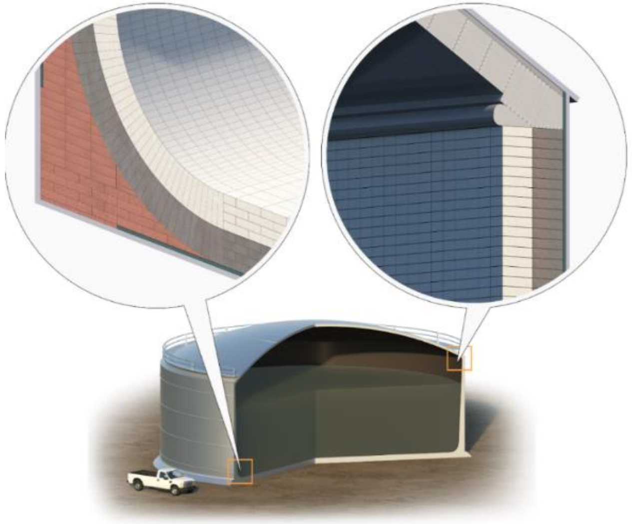
Sodium/Salt Heat Exchanger



Challenge

800C compatibility between Sodium and high nickel alloys is not well known

2-Tank Storage

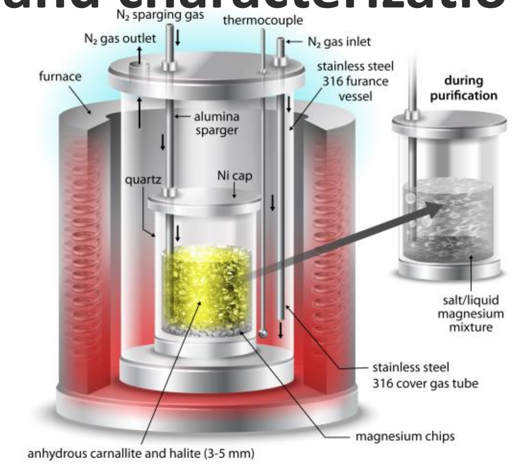


Challenge

Salt vapor pressure is much higher than expected

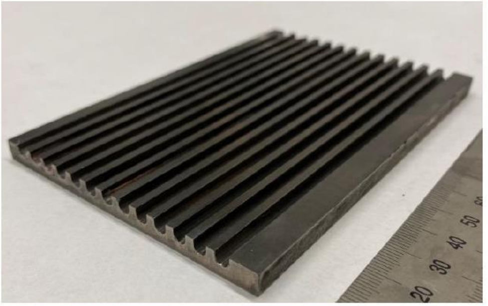
Related Liquid Pathway Accomplishments

Chloride salt purification, handling, and characterization

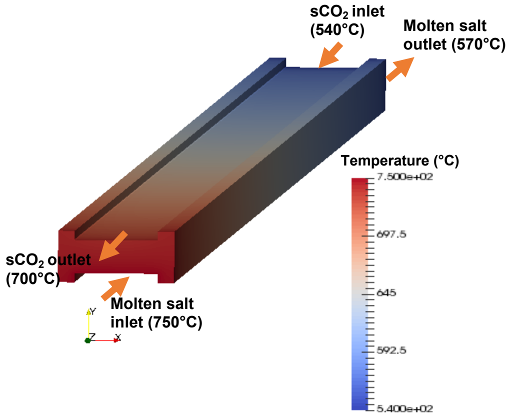


Oak Ridge, Savannah River, NREL, RPI, et al

Novel Heat Exchanger Design and Materials

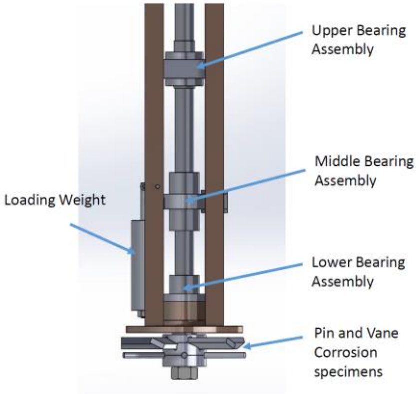


Purdue U. – Melt infiltration synthesis of ceramic/metal composites



Argonne – Additive manufacturing of SiC/Si HXers

Pump and Valve Component Development



Powdermet, U. Wisconsin, Sulzer

Sandia, Flowserve – High-temperature Liquid Valve Design

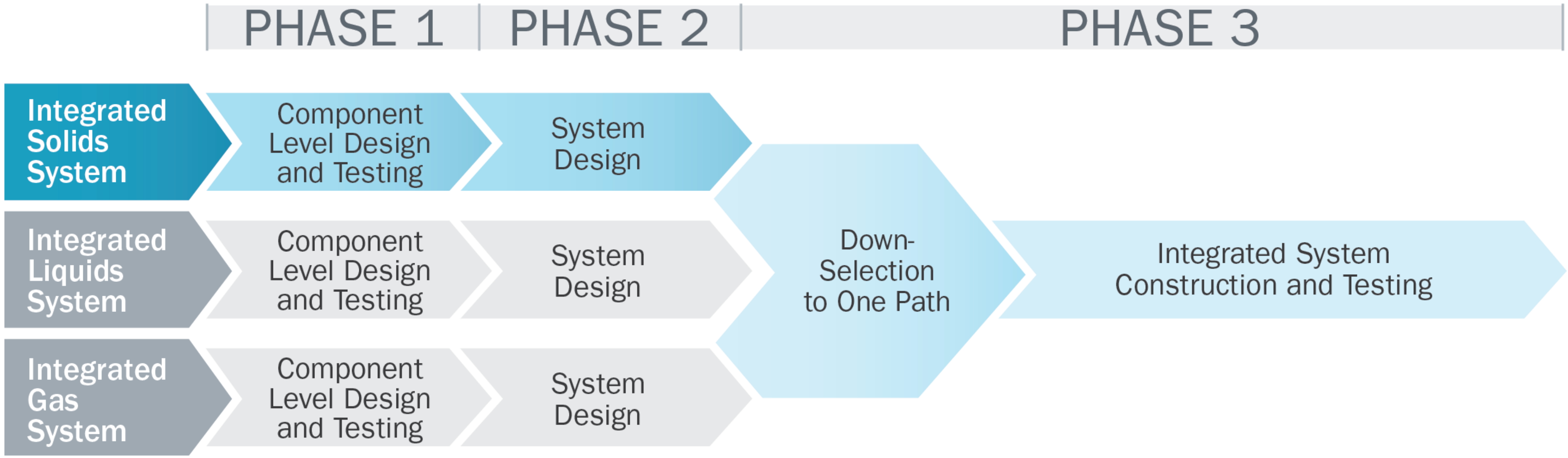
MIT, Purdue, Flowserve

Solid Particle Gen3 CSP Pathway

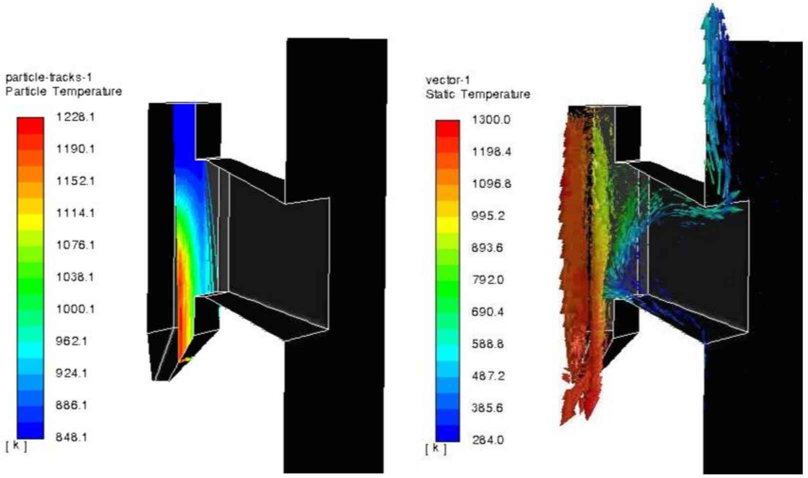
TOPIC 1

- Sandia National Laboratories

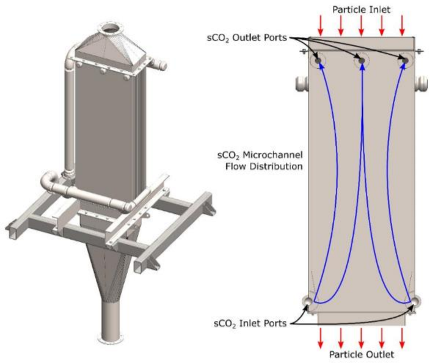
Sandia National Laboratories



Receiver Design and Modelling

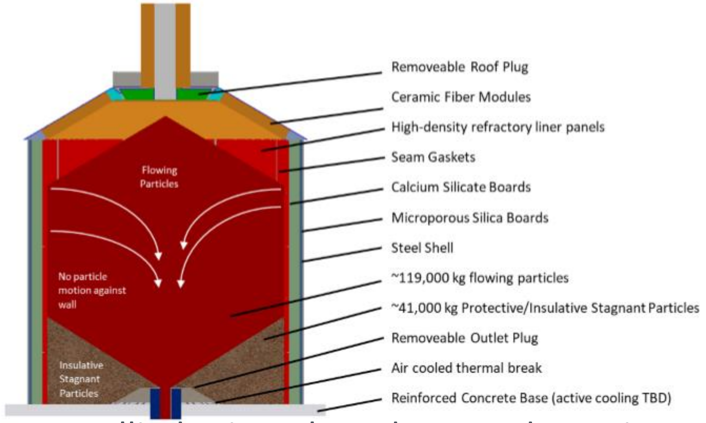


Particle – sCO2 Heat Exchanger



Contributors: VPE and Solex

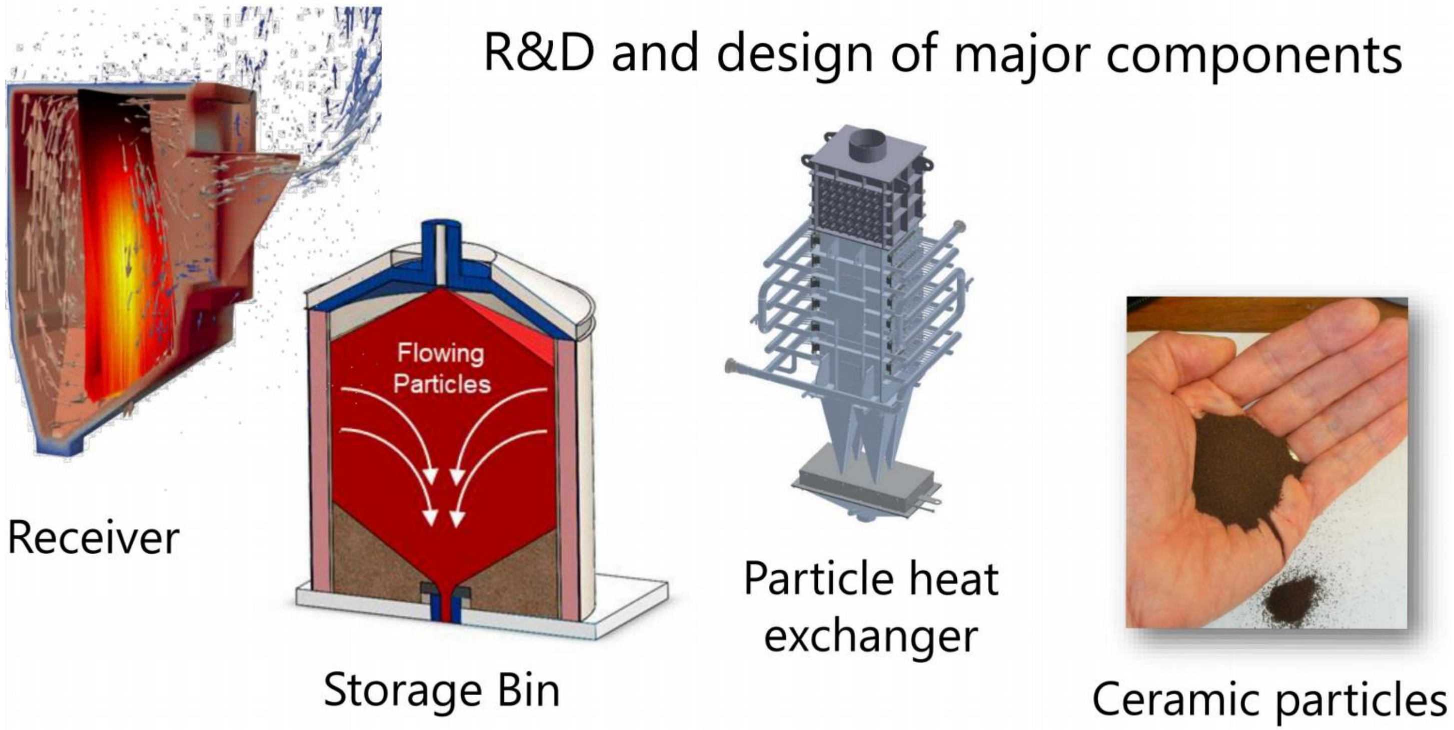
Thermal Energy Storage (Particle Silo)



Contributors: Allied Mineral Products and Matrix PDM

State of the technology – Solid Pathway

R&D and design of major components



Ho, Clifford K. Gen 3 Particle Pilot Plant (G3P3): Integrated High-Temperature Particle System for CSP (2020 SETO Peer Review poster). OSTI ID 1770059

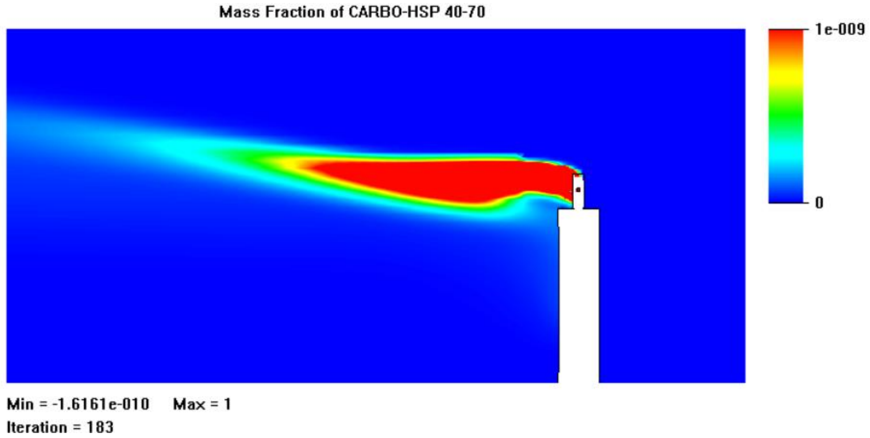
Critical Advancements

- Substantial development of **wind tolerant** open particle **receiver**
- Robust understanding of high temperature **particle handling**, heat transfer, flow, and lifetime
- Sustained effort to demonstrate greater than 300 W/m^2 K moving packed bed **particle to sCO_2 HX**
- Original **conceptual design of 100 MW system** and components
- Compatible with **5¢/kWh LCOE** target

Remaining Challenges: • Robust receiver operation and scale up; • Heat Exchanger performance and cost improvement; • TES and particle media cost reduction; • High Temperature Skip Hoist

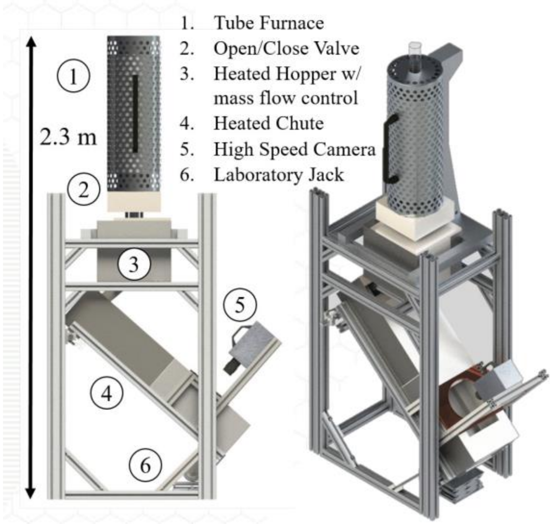
Related Solid Particle Pathway Accomplishments

Particle Receiver Characterization



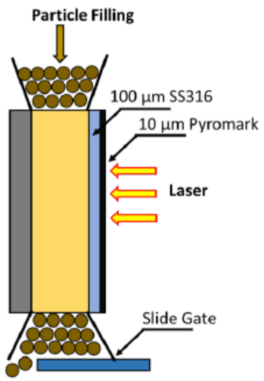
Sandia/UNM – Characterization of Convective and Particle Losses

Particle Flow Characterization



Georgia Tech (Loutzenhiser) – Advanced Characterization of Particulate Flow

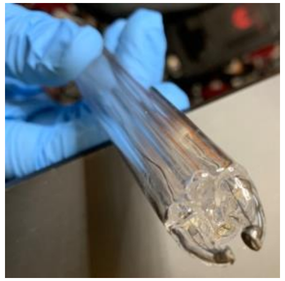
Material Metrology and Testing



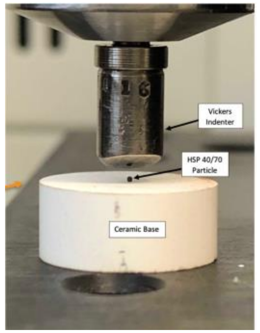
UCSD (Chen) - Modulation Photothermal Radiometry (MPR)

Laser Flash

3-omega



Georgia Tech (Yee) – Thermophysical Properties Database of Gen3 CSP Materials



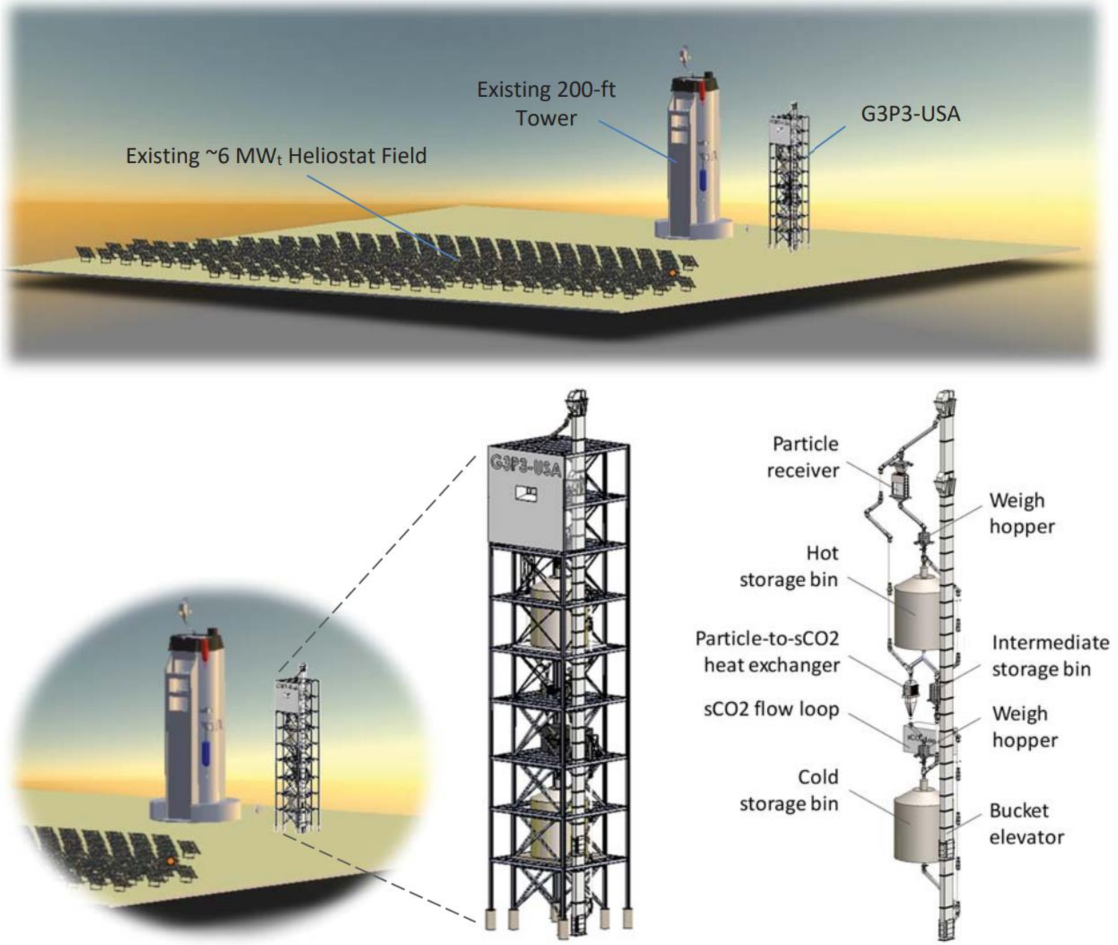
U. Tulsa – Development of GEN3 Durability Life Models

Review Process / Selection Criteria

1. Critical technology risks addressed to advance and succeed in Phase 3.
2. Project management and technical capabilities of the awardees to accomplish Phase 3 activities. Preparation for construction.
3. Merit of future (100 MW scale) Gen 3 System to achieve LCOE targets and the likelihood of market adoption.
4. Extent to which the proposed Phase 3 activities will de-risk technology concerns.
5. Extent to which the proposed Phase 3 results will de-risk commercial adoption of Gen3 CSP

Pathway Selection: Gen 3 Particle Pilot Plant (G3P3)

G3P3 USA



G3P3 KSA

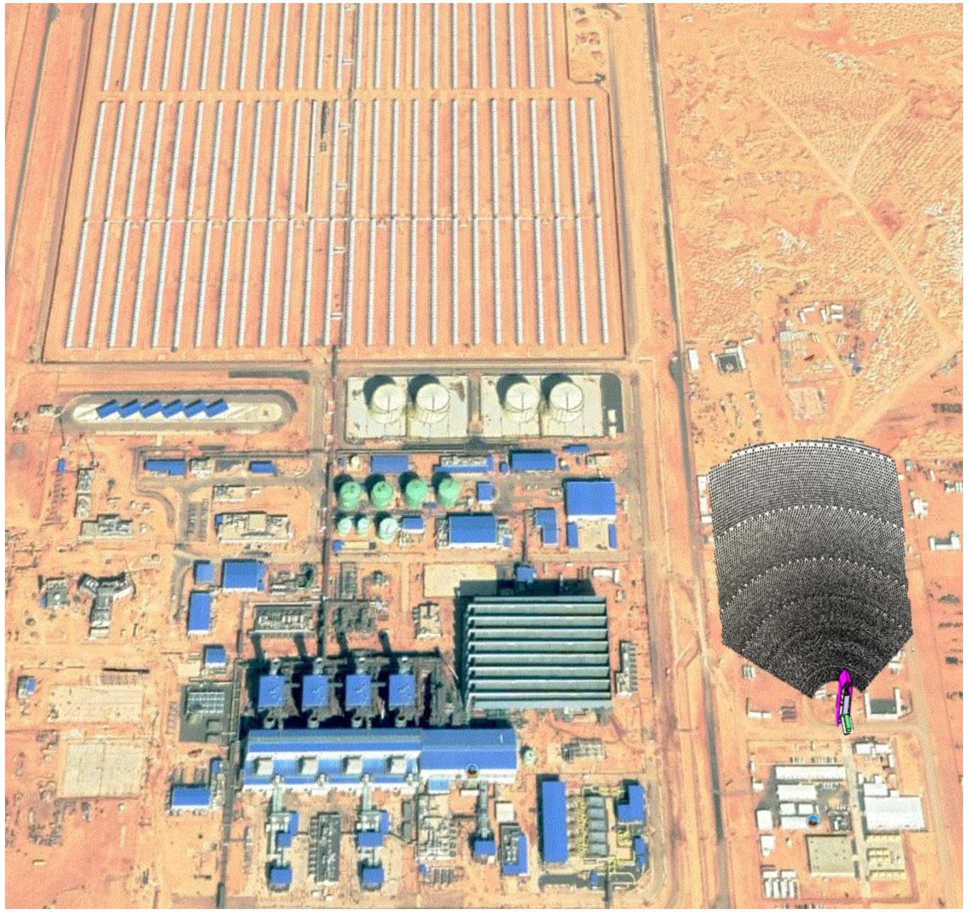
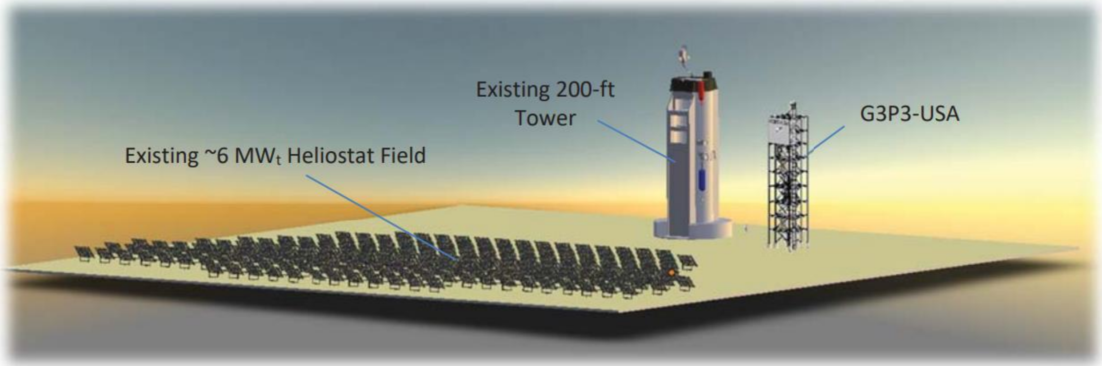


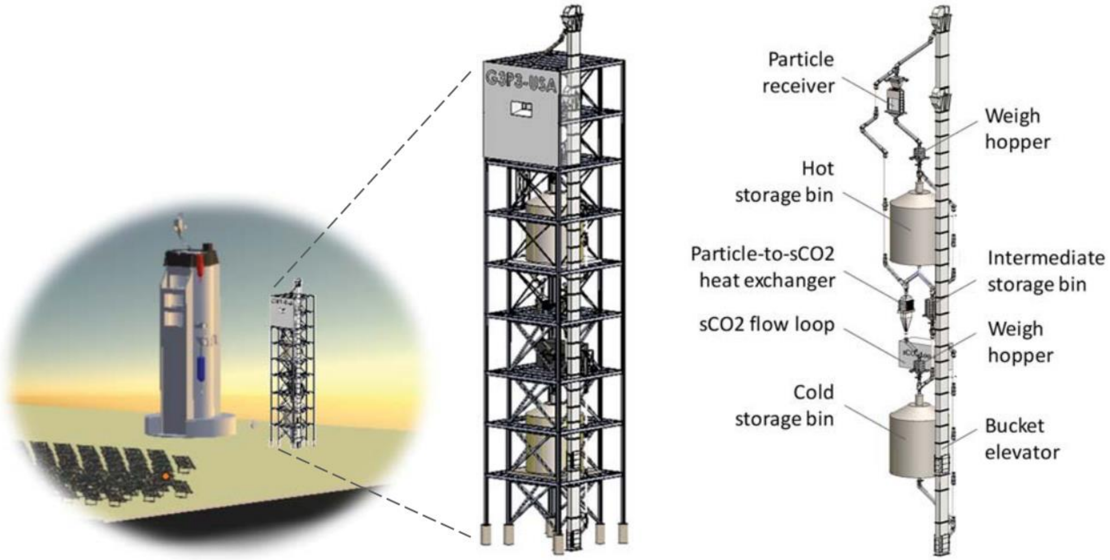
Image from Hany Al-Ansary – King Saud University

Ho, C. K., Albrecht, K. J., Yue, L., Mills, B., Sment, J., Christian, J., & Carlson, M. (2020, December). Overview and design basis for the Gen 3 Particle Pilot Plant (G3P3). In AIP Conference Proceedings (Vol. 2303, No. 1, p. 030020). AIP Publishing LLC.

Pathway Selection: Gen 3 Particle Pilot Plant (G3P3)

G3P3 USA





Solid Pathway Strengths

- System simplicity for construction, operation, and reliability
- Wide operating range and opportunity for further temperature increases
- Potential relevance to other solar thermal applications

Ho, C. K., Albrecht, K. J., Yue, L., Mills, B., Sment, J., Christian, J., & Carlson, M. (2020, December). Overview and design basis for the Gen 3 Particle Pilot Plant (G3P3). In AIP Conference Proceedings (Vol. 2303, No. 1, p. 030020). AIP Publishing LLC.

Future Needs for Gas and Liquid Pathways

Gas

- Design of robust, high-thermal-efficiency receivers for high-flux applications, continue testing to validate
- Continued development of particle-to-gas heat exchangers
- Particle TES design could benefit a wide variety of future applications using indirect HTFs
- System designs needed to minimize parasitics (pressure drop)

Liquid

- Chloride salt is a promising low-cost TES media for multiple applications
- TES tank development and chloride corrosion detection and control needs to be scaled up and validated
- Na receivers integrated with nitrate salt TES may lead to future adoption of chlorides

- Currently available materials impose significant flux limitations on indirect receivers due to thermomechanical property limitations

Particle System Research Opportunities

- Alternate receiver designs may be needed for thermochemical applications where controlled environments are needed
- Particle cost and performance improvement are significant sensitivities to LCOE
- Particle handling and flow control needs to be cost effective and reliable
- Scaling up – system architectures and components need to be optimized and tested at MW-scale, potentially as part of the G3P3 system
- Significant opportunities to improve heat exchanger cost and performance
- Direct receivers and particle TES couple well with large cycle ΔT – can particle systems be optimized to use full temperature range down to ambient?
- Beyond electricity – long duration energy storage, and solar thermochemical applications

Gen3 Summit Goals

- Dissemination of Gen3 pathway designs and project conclusions
  - Project summaries available on our website: https://bit.ly/gen3-summit-2021
- Discussion of remaining gaps and research opportunities
  - Moderated panel discussions, webex chat and Q&A

Gen3 CSP Summit Agenda – Wednesday, August 25

Time (ET)	Session
11:00AM–12:00PM	**SETO Introduction and Overview of the Gen3 CSP Program** *Avi Shultz, Program Manager, CSP, Solar Energy Technologies Office*
12:00PM–1:00PM	**Track A: High-Temperature Nickel-Based Alloys** **Track B: Solid Particle Receivers**
1:00PM–1:30PM	**Parallel Session Discussion**
1:30PM–2:00PM	**Break**

Gen3 CSP Summit Agenda – Wednesday, August 25

Time (ET)	Session
2:00PM–3:00PM	**Gen3 CSP Liquid Pathway**
3:00PM–4:00PM	**Track A: High-Temperature Nickel-Based Alloys** **Track B: Solid Particle Characterization and Handling**
4:00PM–4:30PM	**Parallel Session Discussion**

Gen3 CSP Summit Agenda – Thursday, August 26

Time (ET)	Session
11:00AM–12:00PM	**Gen3 CSP 'Gas' Pathway**
12:00PM–1:00PM	**Track A: Additive Manufacturing of Gen3 CSP Components** **Track B: Metrology and Characterization of High-Temperature Media and Materials**
1:00PM–1:30PM	**Parallel Session Discussion**
1:30PM–2:00PM	**Break**

Gen3 CSP Summit Agenda – Thursday, August 26

Time (ET)	Session
2:00PM–3:00PM	**Gen3 CSP Solid Particle Pathway**
3:00PM–4:00PM	**Track A: Solid Particle Heat Exchangers** **Track B: Components for Molten Chloride Systems**
4:00PM–4:30PM	**Parallel Session Discussion**

SETO CSP team

Technology Managers

Kamala Raghavan, PhD

Rajgopal 'Vijay' Vijaykumar, PhD

Matthew Bauer, PhD

Andru Prescod, PhD,
On contract from Mantech

Shane Powers
On contract from Mantech

Levi Irwin, PhD
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Science and Technology Policy Fellow

Nikkia McDonald, PhD

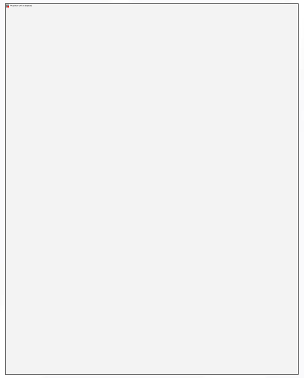
Financial Analyst

Patty Clark, MBA
On contract from Allegheny S&T

Technical Project Officer

Christine Bing, MBA

Operations



Meisha Baylor
On contract from Red Horse

QUESTIONS?

Avi Shultz

avi.shultz@ee.doe.gov

Program Manager, CSP


Gen3CSP
Bringing together the people and the pieces for an
INTEGRATED CSP SYSTEM