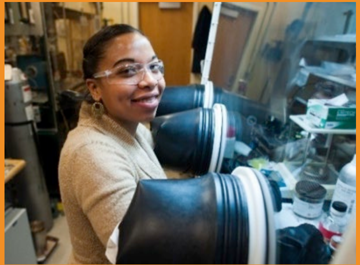
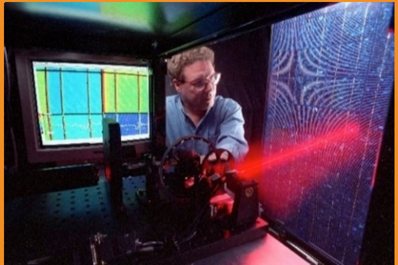
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE




Concentrating Solar Thermal Power Research and Development Overview

Dr. Avi Shultz, Program Manager

Thermal Energy Storage Workshop

Idaho Falls, ID

July 23, 2019

SETO overview

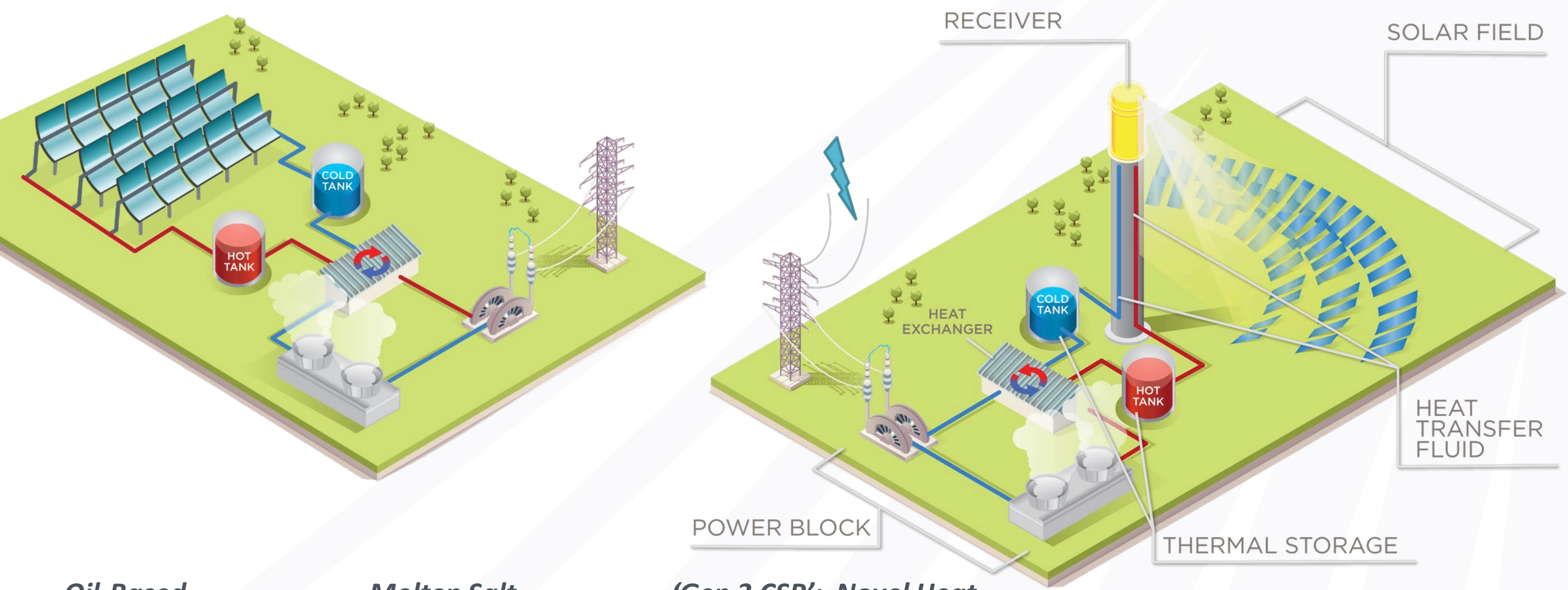
WHAT WE DO

The U.S. Department of Energy's Solar Energy Technologies Office supports early-stage research and development of solar technologies while focusing on **grid reliability**, **resilience**, and **security**.

HOW WE DO IT

The office uses a competitive solicitation process to addresses critical research gaps, ensuring the solar industry has the technological foundations needed to **lower solar electricity costs**, **ease grid integration**, and **enhance the use and storage of solar energy**.

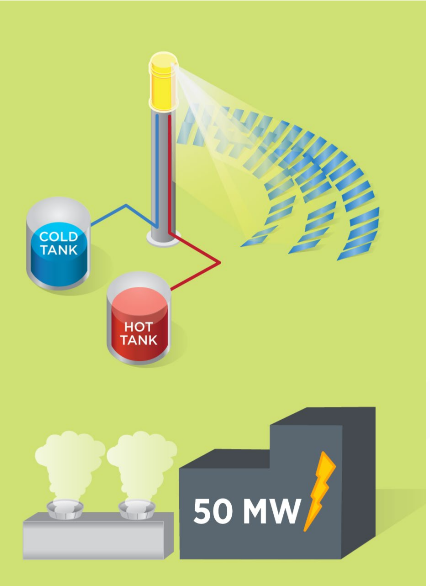
CSP with Storage is Solar Energy On-Demand



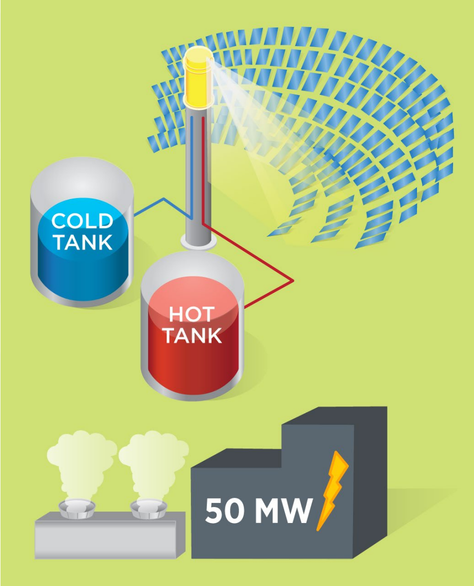
Oil-Based Troughs with steam rankine cycle (~400 °C) → *Molten Salt Towers with steam rankine cycle (~565 °C)* → *'Gen 3 CSP': Novel Heat Transfer Media with advanced power cycle (>700 °C) @ 5¢/kWh*

CSP: Flexible Designs for an Evolving Grid

‘Peaker’
(≤6 hours of storage)



‘Baseload’
(≥12 hours of storage)



By choosing the size of the solar field and thermal energy storage, the same CSP technology can be configured to meet evolving demands of the grid

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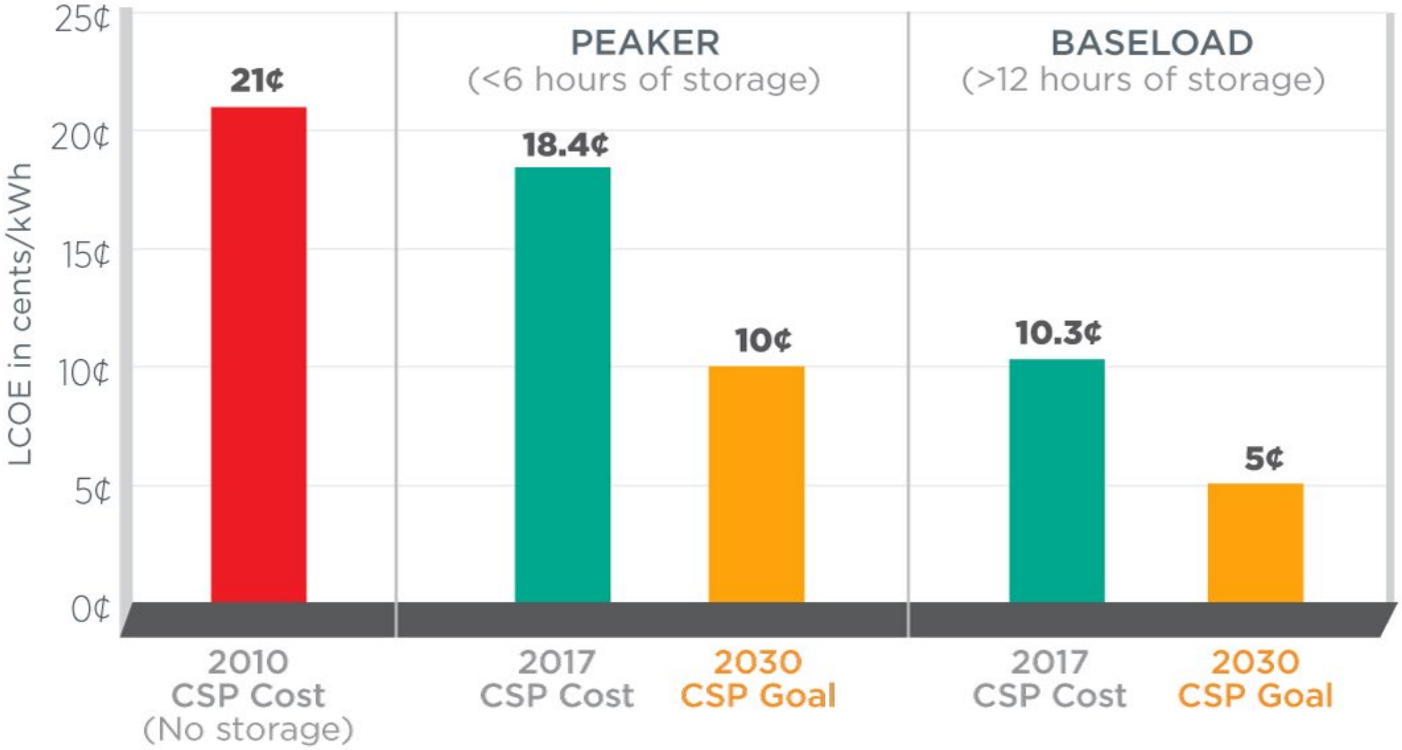
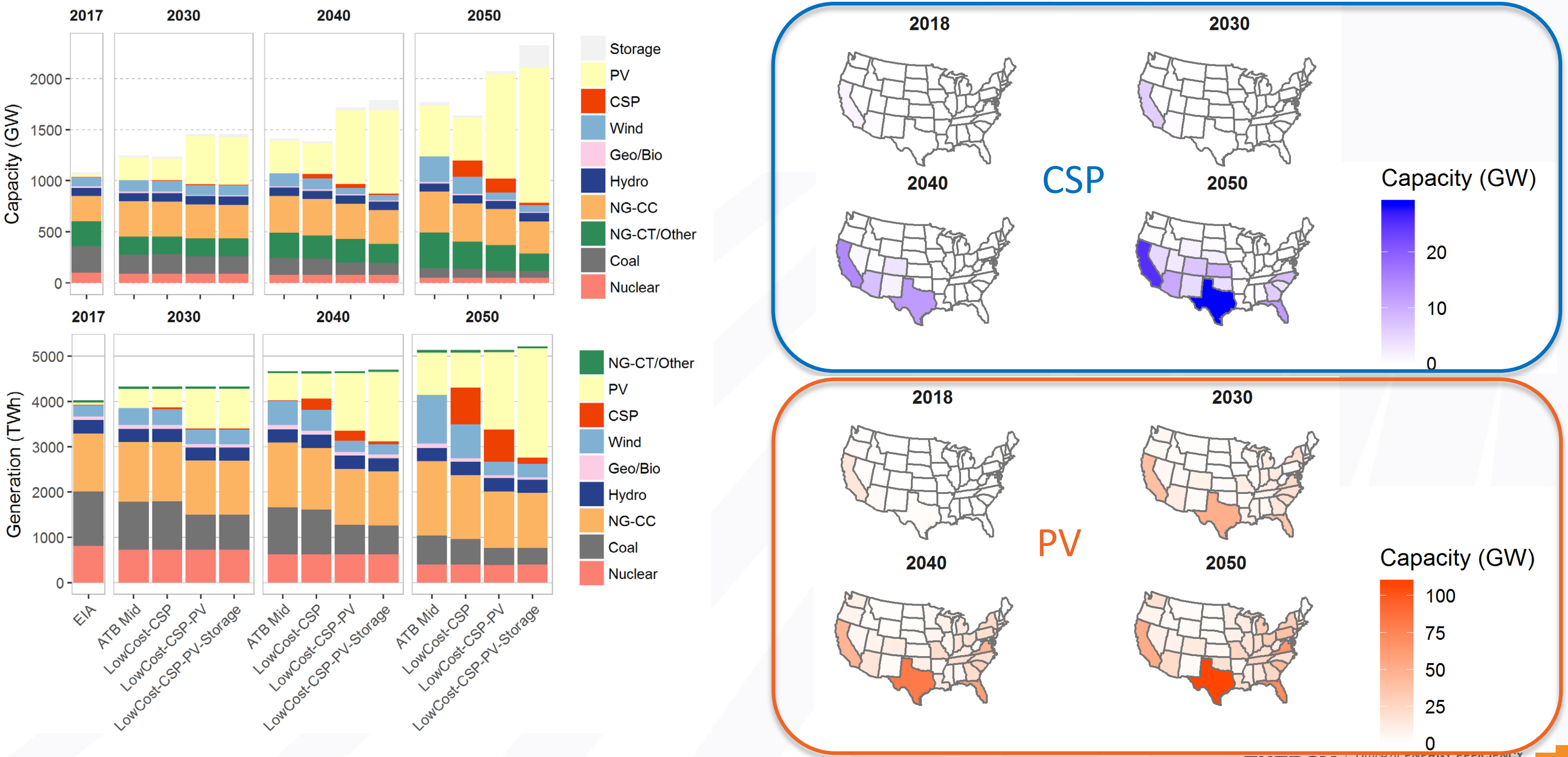
2030 DOE Levelized Cost of Electricity Targets



Potential CSP Deployment in the US if DOE CSP and PV 2030 Cost Targets are Achieved



Murphy, et al. **2019**, NREL/TP-6A20-71912

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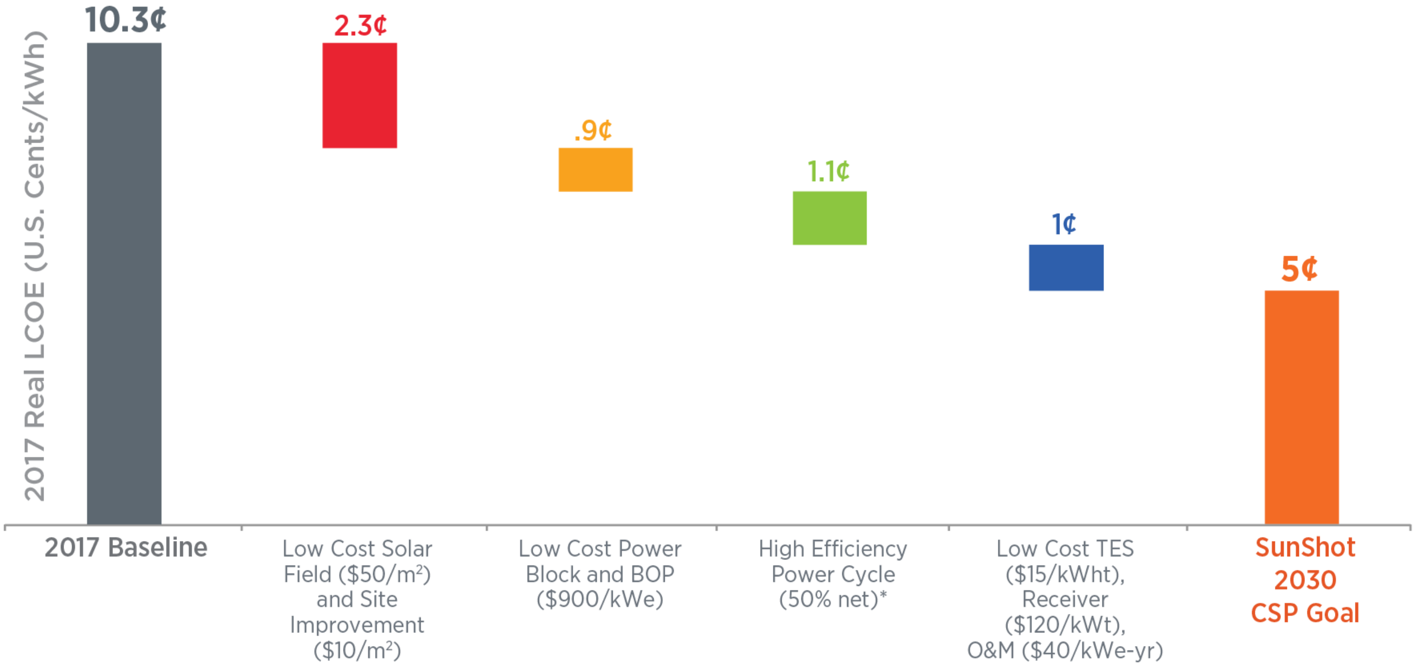
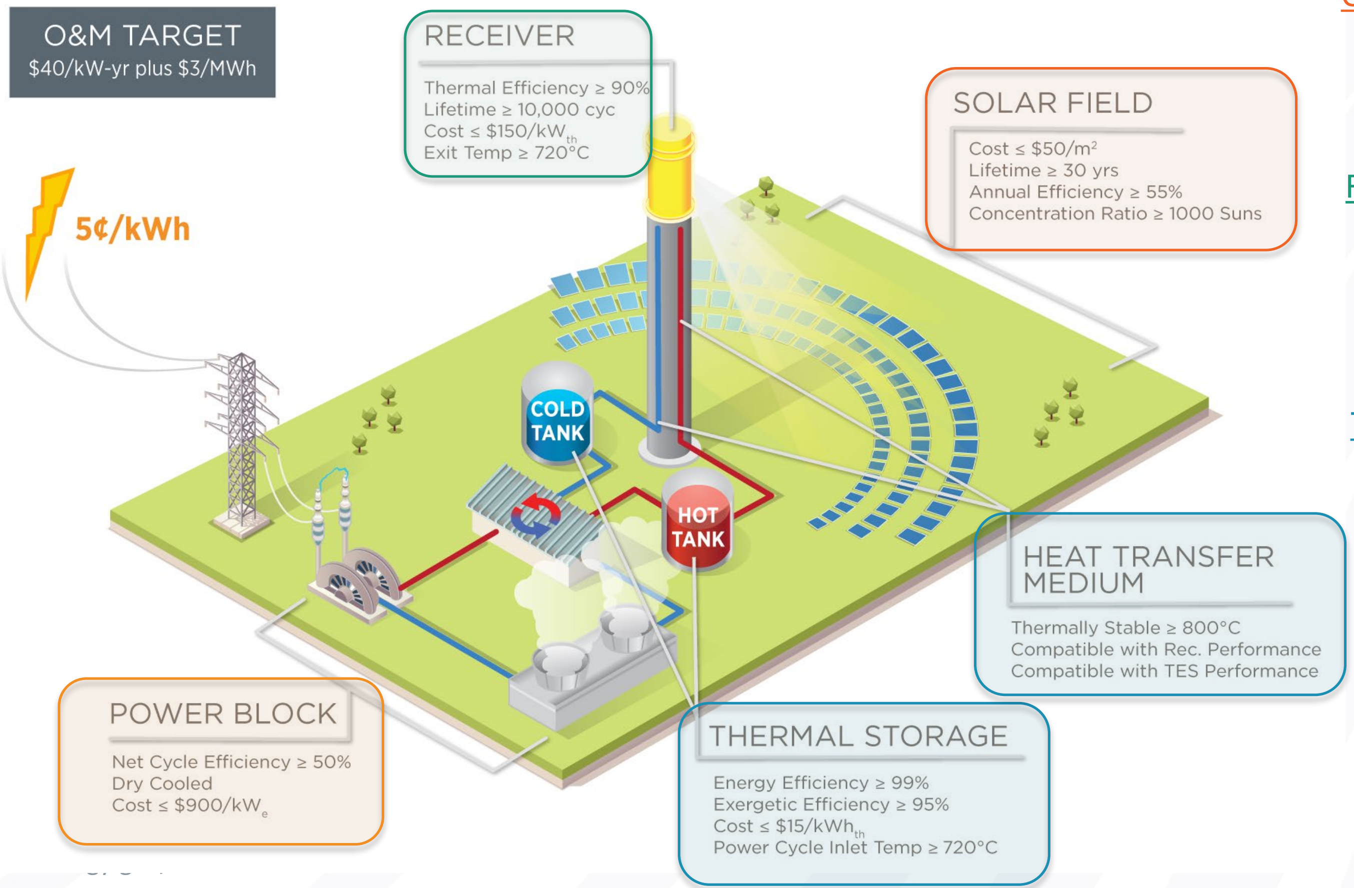
A Pathway to 5 Cents per KWh for Baseload CSP



*Assumes a gross to net conversion factor of 0.9

CSP Program Technical Targets



Collector Field

- Optical Physics
- Structural design and dynamics
- Manufacturing and automation
- Sensors and control

Receivers

- Optical properties
- Coatings
- High temperature materials
- Chemistry
- Heat Transfer, Fluid Mechanics

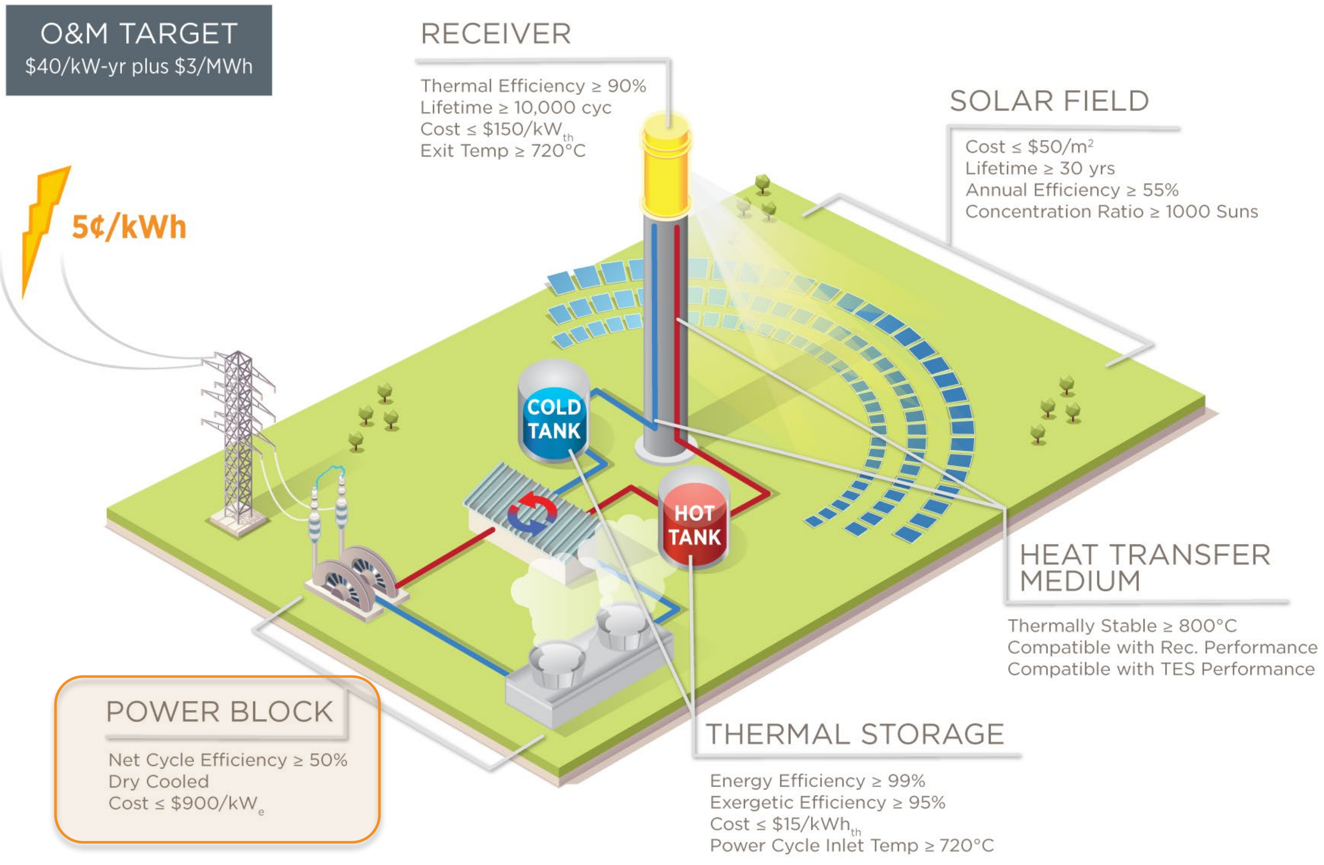
TES and HTF

- Chemistry
- High temperature materials
- Materials Science
- Heat Transfer, Fluid Mechanics

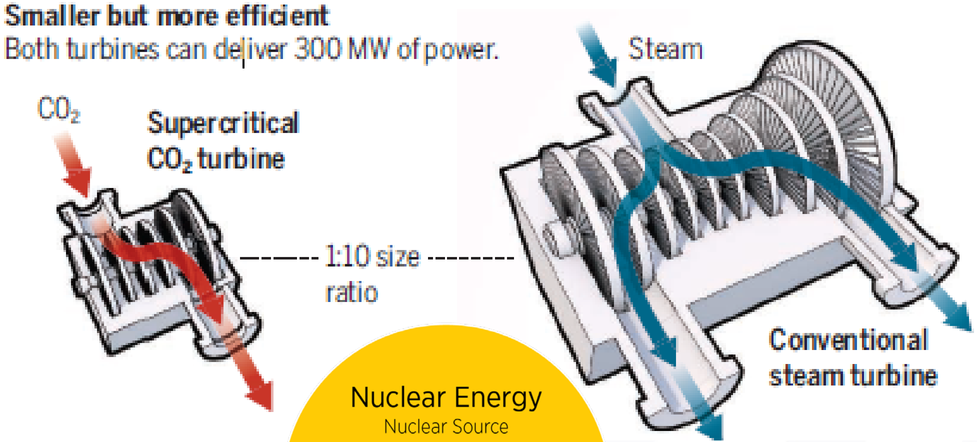
Power Block

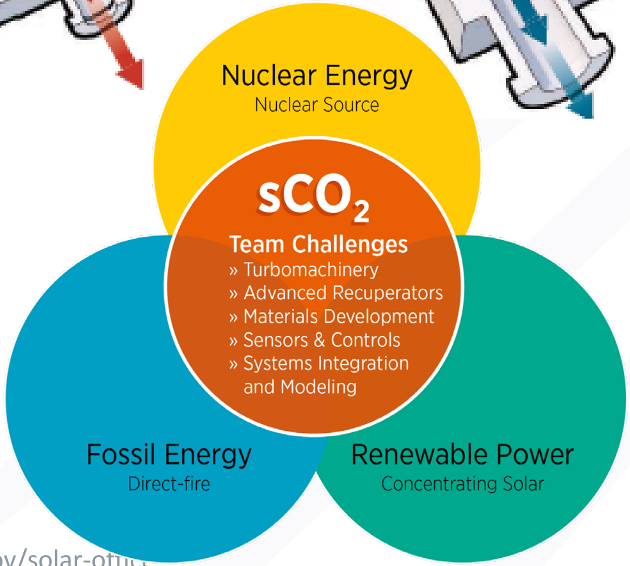
- High temperature materials
- Turbomachinery
- Manufacturing and automation
- Sensors and control

CSP Program Technical Targets



Next Generation CSP will Leverage Next Generation Power Cycles





Advantages of the sCO_2 Brayton Cycle:

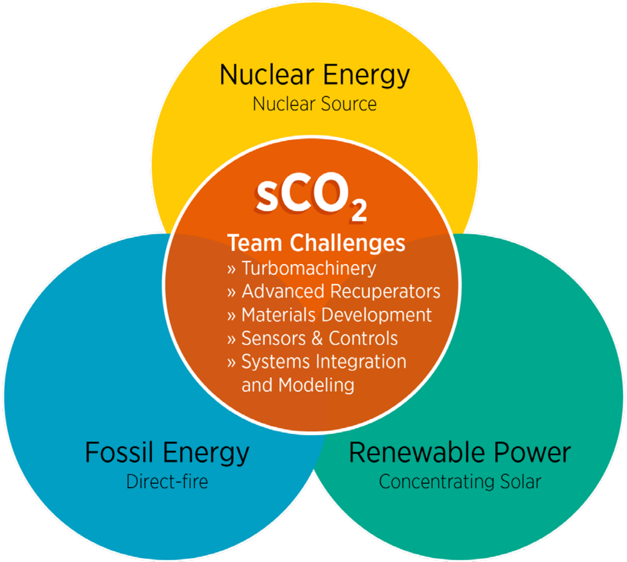
- Higher Efficiency (50% ~720 C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- Scalability (Sub 100 MW)
- Operational Simplicity (No Phase Change)

CSP Specific R&D Challenges

- Higher Temperature Thermal Transport System
- Expanding Temperature Change (Sensible TES)
- Ambient Temperature Variability (Dry Cooling)
- Variable Solar Resource

Irwin, Le Moullec. "Turbines can use CO_2 to cut CO_2." *Science* 356.6340 (2017): 805-806.

Next Generation CSP will Leverage Next Generation Power Cycles



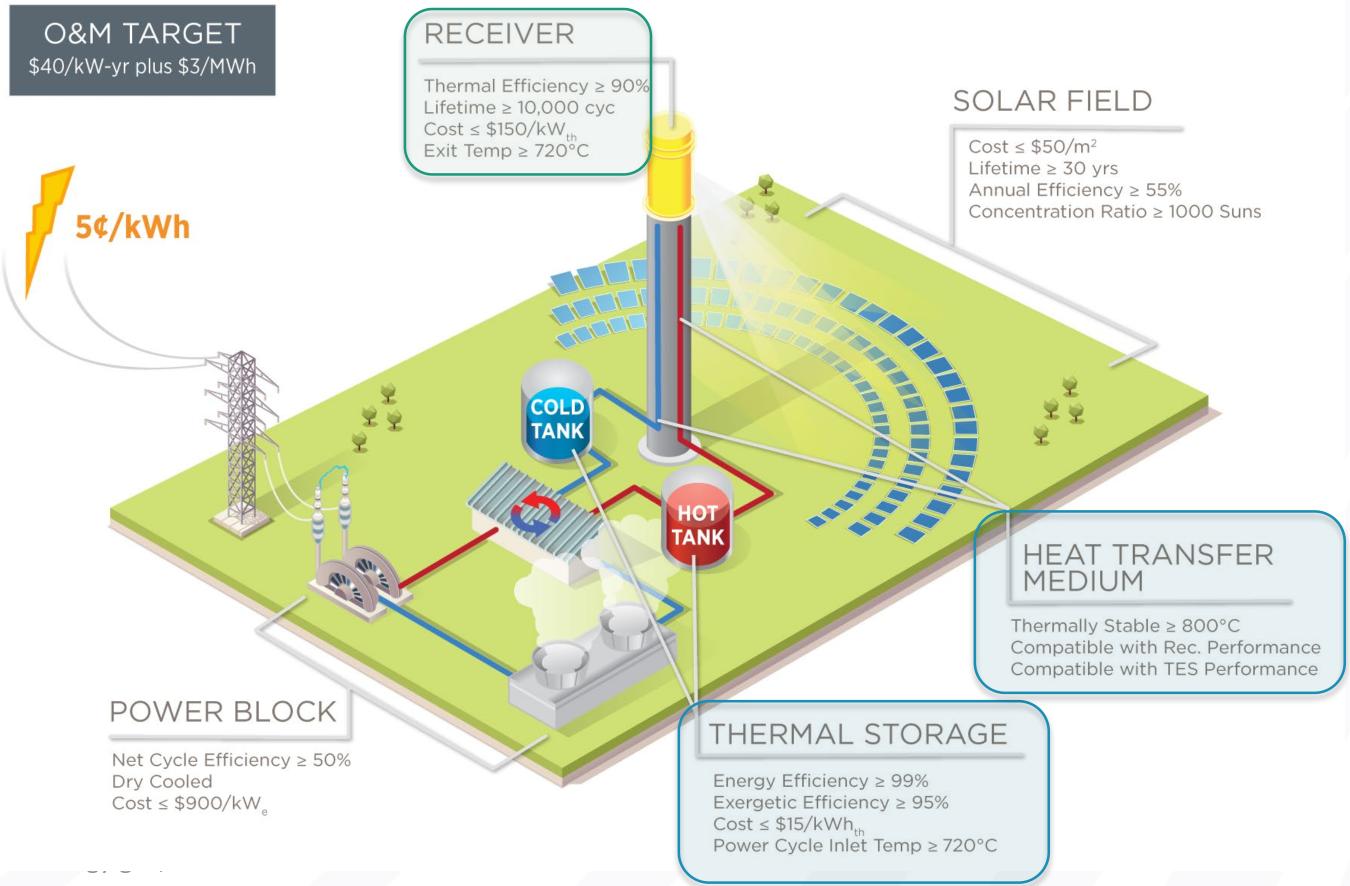
Supercritical CO_2: a dense, compressible fluid

- Compact turbomachinery
- Good compatibility with dry cooling
- Fewer loss mechanisms and parasitics

10 MW_e STEP Test Facility

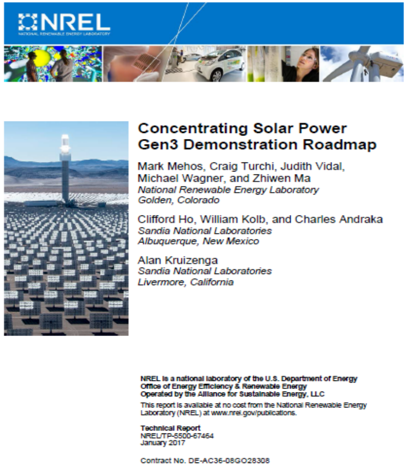
- $100 M Program managed by FE begun in 2017
- Awarded to Gas Technology Institute, facility located at Southwest Research Institute
- Capable of testing all components of Cycle Integrated with controls & instrumentation
- Resolve issues common to multiple potential heat sources
- Reconfigurable facility capable of 700 °C and 300 bar operation

CSP Program Technical Targets



Gen3 CSP: Raising the Temperature of Solar Thermal Systems

$$\eta = 1 - \frac{T_C}{T_H}$$



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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

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.

Technical Report
NREL/TP-5500-67464
January 2017

Contract No. DE-AC36-08GO28308

http://www.nrel.gov/docs/fy17osti/67464.pdf

Gen3 CSP Topic 1 Awardees

Sandia National Laboratories

DOE Award (P1-2): $9,464,755

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

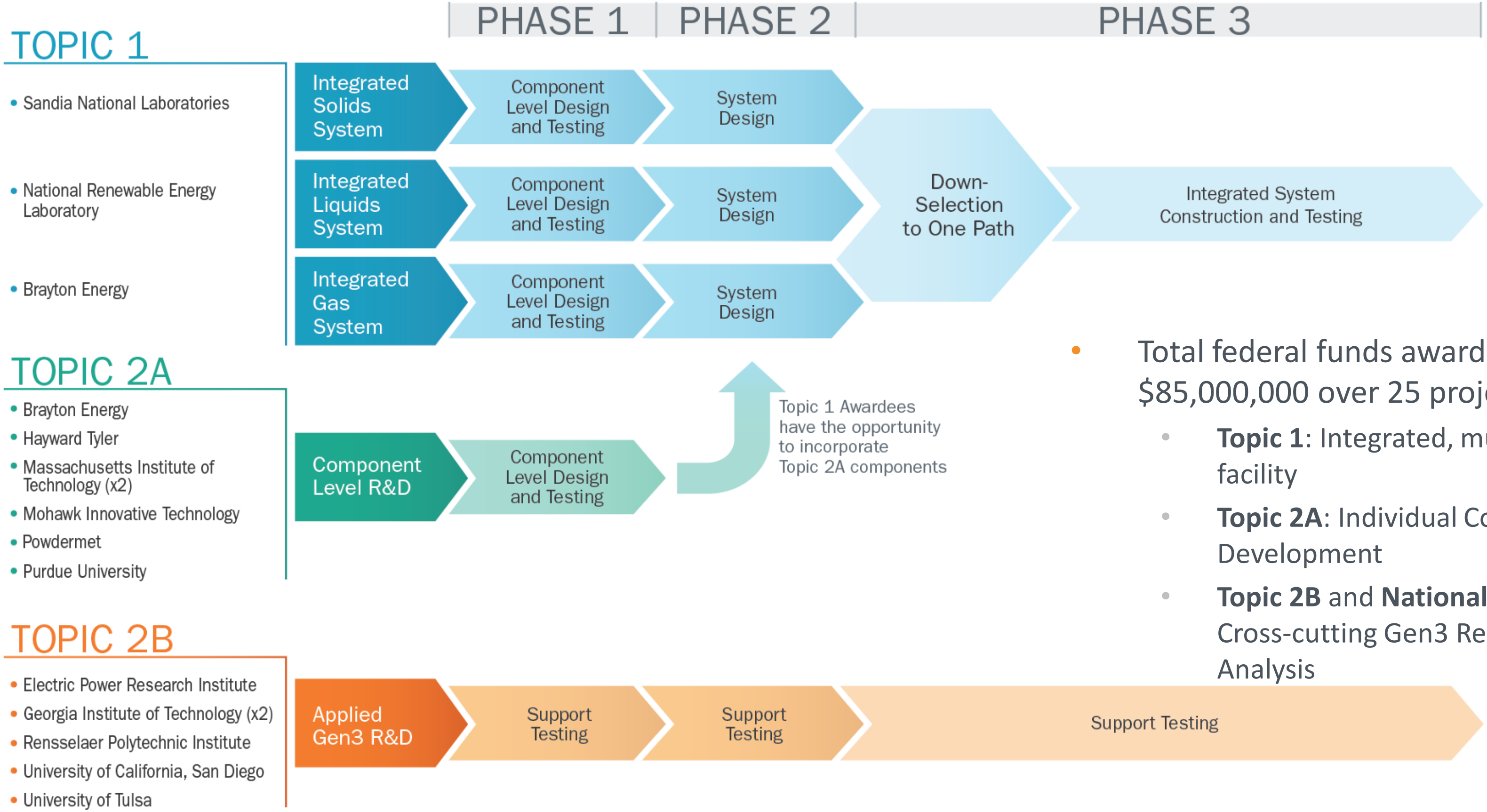
DOE Award (P1-2): $7,035,309

BraytonEnergy

DOE Award (P1-2): $7,570,647

COLLECTOR FIELD	RECEIVER	THERMAL TRANSPORT	THERMAL STORAGE	HEAT TRANSFER MEDIA	HEAT EXCHANGE	POWER CYCLE
SOLID MEDIA	• Thermal Efficiency: • Particle Loss • Flow Velocity Control and Monitoring	• Reliability • Mechanical and Thermal Efficiency • Scalability • Insulation	• Charging and Discharging Particle loss, Efficiency, Scalability	• Particle Attrition • Optimized Performance Character	• Low Cycle Fatigue • Particle Mass Flow Control • Ramp Rates & Transients	
MOLTEN SALT	• Thermal Conductivity • Thermal Stability • Tube Strength and Durability	• Pipe Material Compatibility • Freeze Recovery • Pumps Valves Seals • Leak Detect	• Corrosion Behavior • Chemistry Monitoring and control • Tank Cost	• Characterize Material Properties • Cost / Supply Chain	• Material Compatibility w/ salt & CO_2 • Freeze Protection • Thermal Ramp Rates	
GAS	• High Pressure Fatigue • Absorptivity Control and Thermal Loss Management	• Recirculator Cost & Operating Power • Large Pipes High Cost	• Storage Concept not Determined	• Low Thermal Conductivity • Low Heat Capacity	• Requires High Area • Multiple Heat Exchangers • Cascading Temperature	

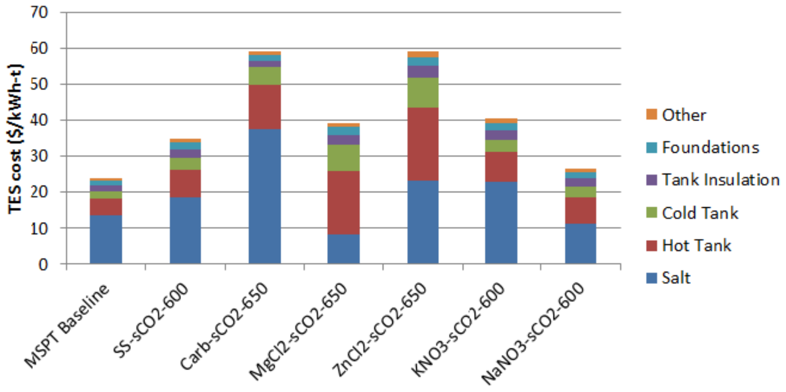
Gen3 CSP Awardees

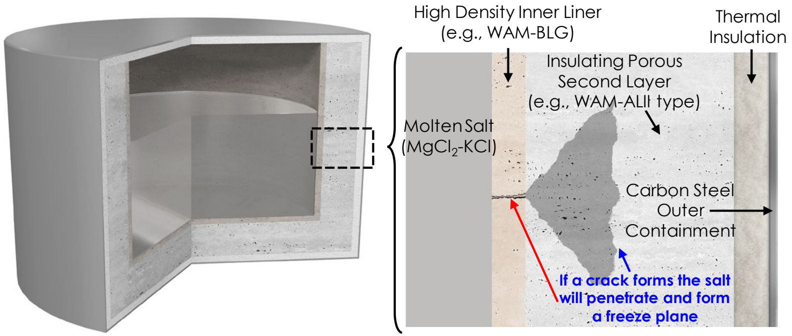


- Total federal funds awarded in 2018: $85,000,000 over 25 projects in 3 Topics:
  - **Topic 1**: Integrated, multi-MW test facility
  - **Topic 2A**: Individual Component Development
  - **Topic 2B** and **National Lab Support**: Cross-cutting Gen3 Research and Analysis

Thermal Energy Storage R&D: Components

TOPIC	PRIME	PI	FOA
Advanced Hot Media Insulation	**SolarReserve**	Bill Gould	**Tech-to-Market (2017)**
	MIT	Asegun Henry	**Gen3 CSP Systems (2018)**
	UCSD	Jian Luo	**SETO FY18 FOA – SIPS**
Hot Salt Pumps	**Powdermet**	Joseph Hensel	**Gen3 CSP Systems (2018)**
	Hayward Tyler	Benjamin Hardy	**Gen3 CSP Systems (2018)**
	MIT	Asegun Henry	**Gen3 CSP Systems (2018)**
Integrated Heat Pump	**NREL**	Joshua McTigue	**SETO FY19-21 Labcall**



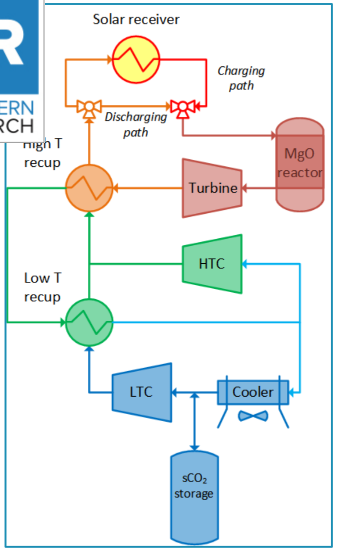


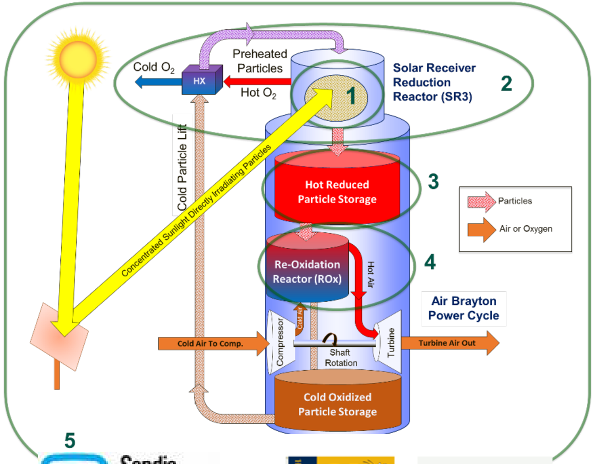
Thermal Energy Storage R&D: Thermochemical

TOPIC	PRIME	PI	FOA
Metal Oxides	Sandia NL	James Miller / Andrea Ambrosini	ELEMENTS (2014)
	Colorado School of Mines	Greg Jackson	ELEMENTS (2014)
Metal Hydrides	Savannah River NL	Ragaiy Zidan	SunShot Lab R&D (2013)
	Brayton Energy	Shaun Sullivan	APOLLO (2015)
Metal Sulfides	Los Alamos NL	Steve Obrey	SuNLaMP (2015)
Metal Carbonates	Southern Research	Andrew Muto	ELEMENTS (2014), APOLLO (2015)
	Echogen	Tim Held	Tech-to-Market (2017)
Ammonia	UCLA	Adrienne Lavine	ELEMENTS (2014)
	Sandia NL	Andrea Ambrosini	FY19-21 Labcall

ECHOGEN power systems

SR SOUTHERN RESEARCH



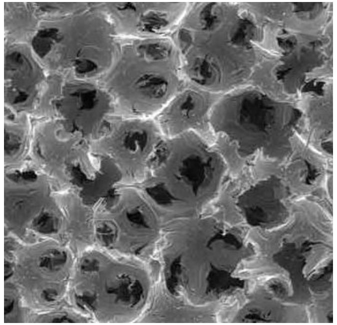


Sandia National Laboratories

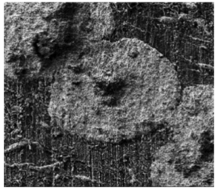
GEORGIA TECH

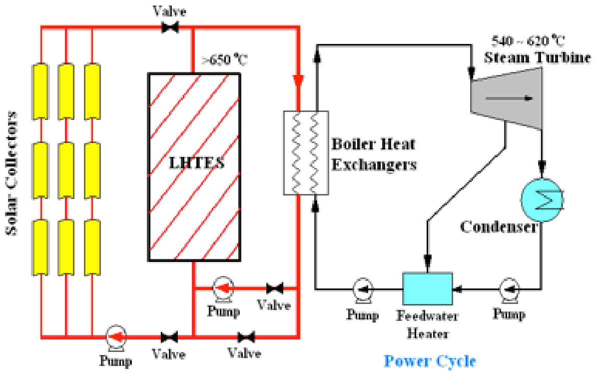
ASU Arizona State University

Thermal Energy Storage R&D: Phase Change Materials



- PI: Dileep Singh
- Developed change materials (PCMs) in combination with new, high thermal conductivity graphite foams funded through **SunShot Lab R&D (2012)** and **APOLLO (2015)**
- Currently being developed into **Gen3 CSP** indirect TES system with Brayton Energy



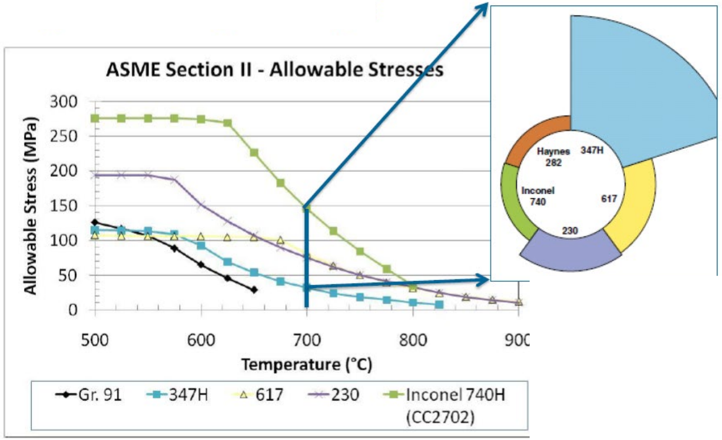


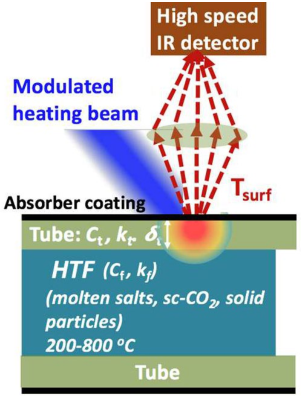
Thermal Energy Storage R&D: Thermal / Materials Characterization

TOPIC	PRIME	PI	FOA
Thermophys. Prop. Of Particles	Sandia NL	Kevin Albrecht	Gen3 Lab Support
	Georgia Tech	Peter Loutzenhiser	Gen3 CSP Systems (2018)
	U. Tulsa	Todd Otanicar	Gen3 CSP Systems (2018)
Thermophys. Characterization	UCSD	Renkun Chen	Gen3 CSP Systems (2018)
	Georgia Tech	Shannon Yee	Gen3 CSP Systems (2018)
Low-Cost Ni-Alloy Mfg	EPRI	John Shingledecker	Gen3 CSP Systems (2018)
	Oak Ridge NL	G. Muralidharan	FY19-21 Labcall

EPRI ELECTRIC POWER RESEARCH INSTITUTE

SPECIAL METALS A PCC Company

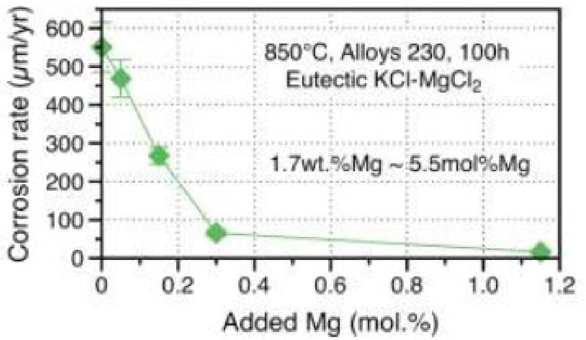




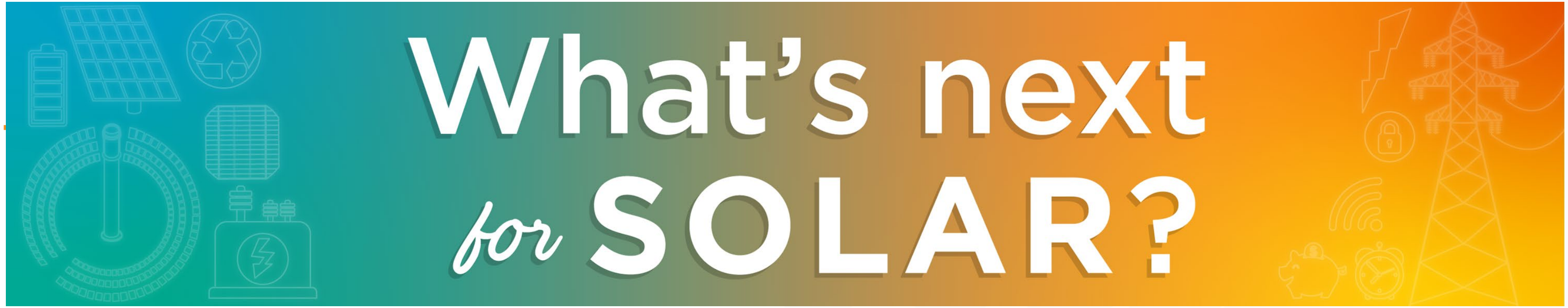
UC San Diego

Thermal Energy Storage R&D: Thermo-physical and -chemical Characterization of Chloride Salts

Topic	PRIME	PI	FOA
Thermo-physical and chemical characterization	**NREL**	Judith Vidal	Gen3 Lab Support (2018)
	Oak Ridge NL	Kevin Robb	Gen3 Lab Support (2018)
Corrosion Characterization	**Oak Ridge NL**	Bruce Pint	Gen3 Lab Support (2018)
	Oak Ridge NL	Gabriel Veith	Gen3 Lab Support (2018)
	Rensselear Polytechnic Institute	Emily Liu	Gen3 CSP Systems (2018)
Corrosion Mitigation	**Savannah River NL**	Brenda Garcia-Diaz	Gen3 Lab Support (2018)
	U. Arizona	Dominic Gervaiso	SETO FY18 FOA
	Purdue University	Kenneth Sandhage	SETO FY18 FOA - SIPS
	Virginia Tech	Ranga Pitchumani	SETO FY18 FOA - SIPS



If salt chemistry – O_2, H_2O content – can be controlled, corrosion can be managed



SETO's FY19 Funding Opportunity Announcement was issued on March 26, 2019

Achieving SETO's priorities across the solar energy technology landscape requires sustained, multifaceted innovation. For our FY19 Funding Program, the office intends to support high-impact, early-stage research in the following areas:

- **Topic 1: Photovoltaics Research and Development**
- **Topic 2: Concentrating Solar-Thermal Power Research and Development**
- **Topic 3: Balance of Systems Soft Costs Reduction**
- **Topic 4: Innovations in Manufacturing: Hardware Incubator**
- **Topic 5: Advanced Solar Systems Integration Technologies**

Topic 2 – Concentrating Solar-Thermal Power Research and Development

Topic 2.1: Firm Thermal Energy Storage ($11 million)

Concepts that expand the dispatchability and availability of CSP plants to provide value to grid operators. Thermal energy storage (TES) systems of interest include:

- Long-term TES systems that store energy for weekly or seasonal dispatch
- Pumped heat electricity storage for CSP and concepts that enable charging of TES via off-peak grid electricity
- Commercializing TES through projects that pursue near-term market adoption

Topic 2.2: Materials and Manufacturing ($11 million)

Solutions that reduce the cost of manufacturing CSP components, encourage the commercialization of new CSP technologies, and support the development of an agile, U.S.-based CSP manufacturing sector.

Topic 2.3: Autonomous CSP Collector Field ($11 million)

Solutions that enable a solar field that can fully operate without any human input, reducing costs and maximizing thermal energy collection efficiency.

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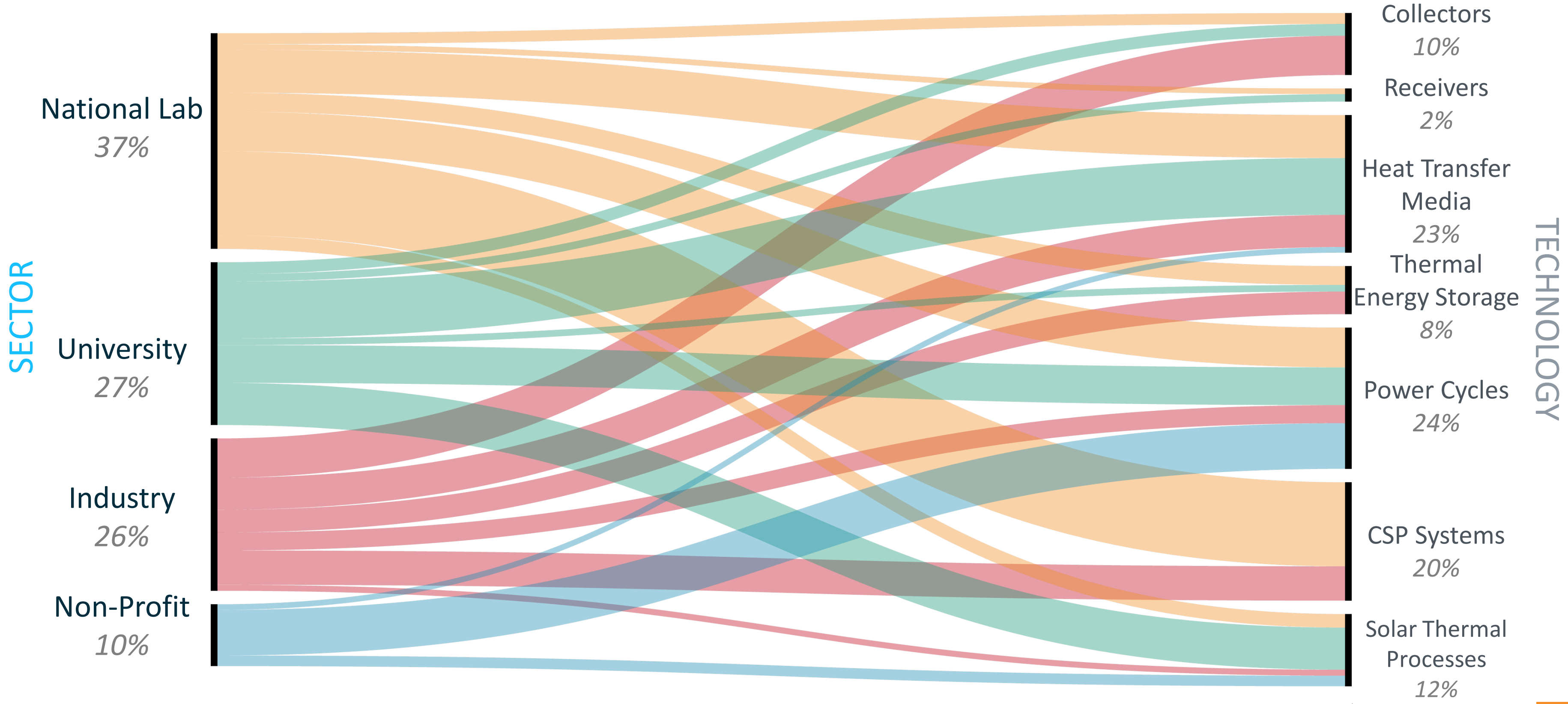
SOLAR ENERGY TECHNOLOGIES OFFICE

Questions?

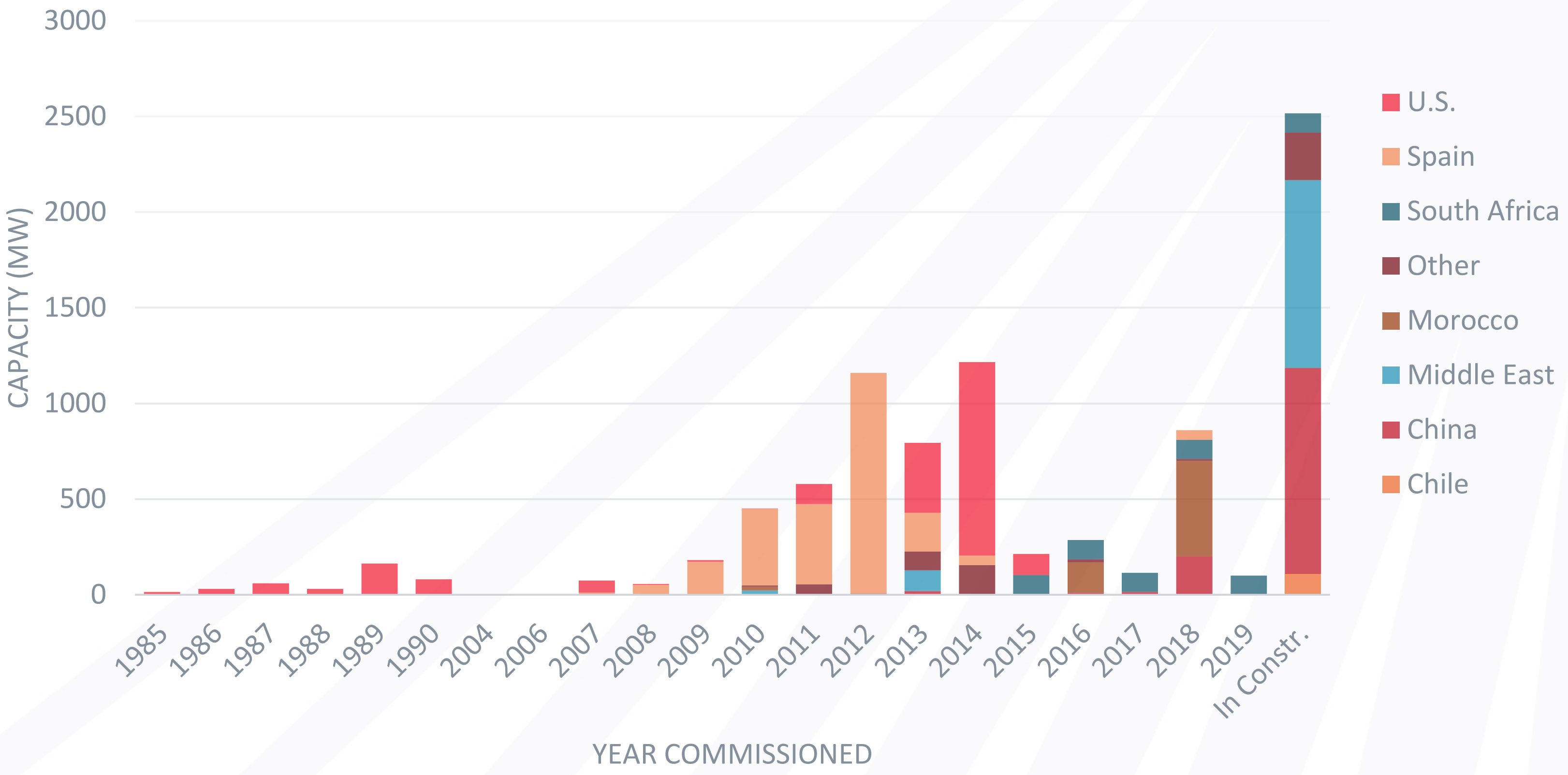
Avi Shultz

avi.shultz@ee.doe.gov
Program Manager, CSP

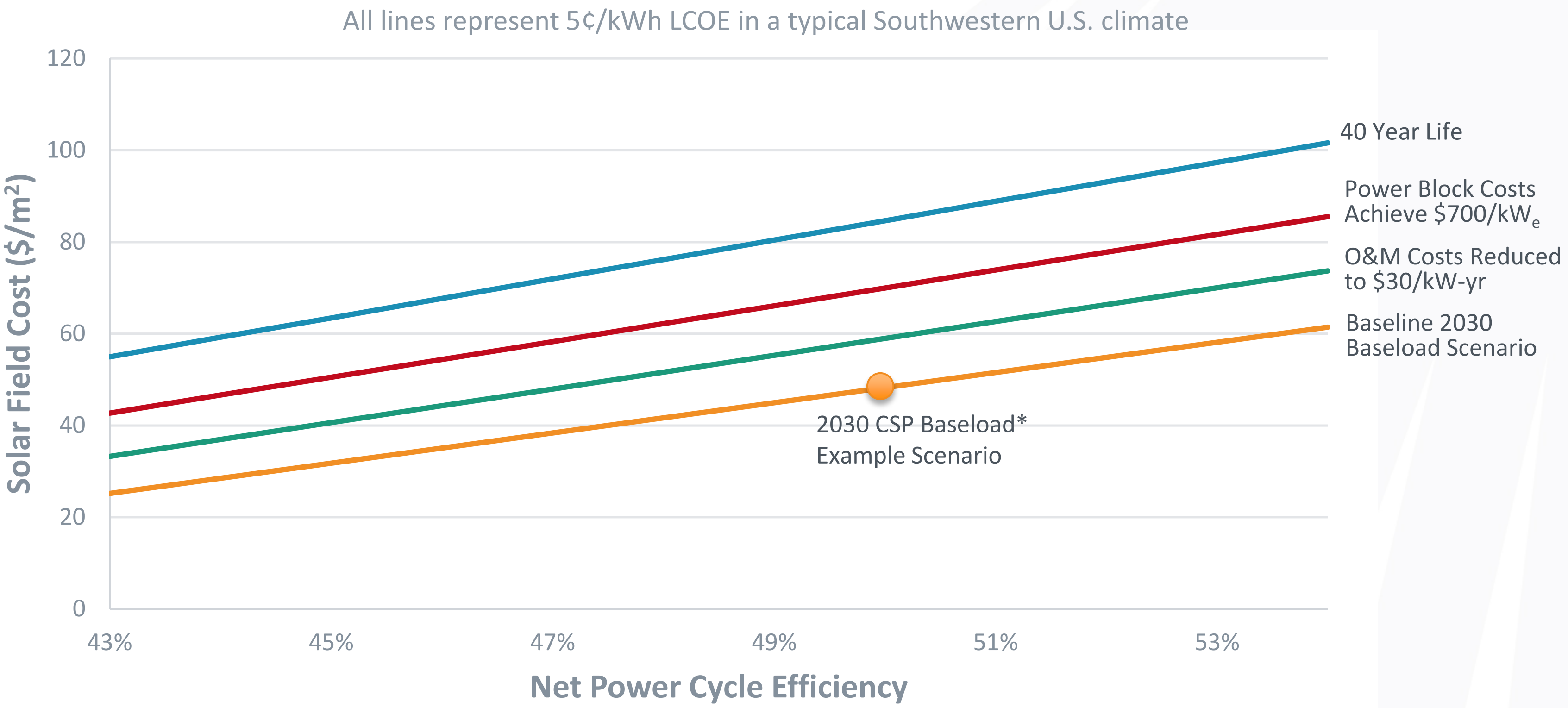
CSP Awardee Breakdown by Funding



CSP is Being Deployed Worldwide



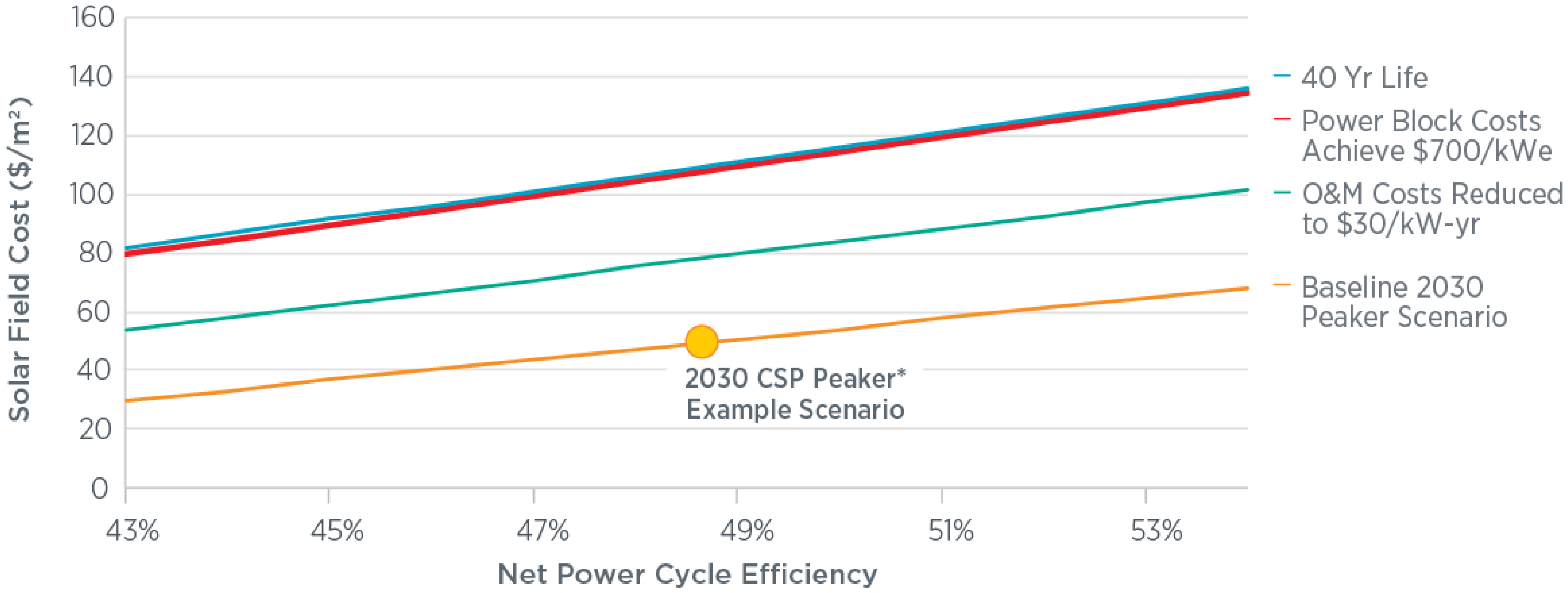
Pathways to Achieving SunShot 2030 Goals



*Baseload power plant is defined as a CSP plant with greater than or equal to 12 hours of storage

Pathways to Achieving SunShot 2030 Goals

All lines represent 10¢/kWh LCOE in a typical Southwestern U.S. climate



*Peaker power plant is defined as a CSP plant with less than 6 hours of storage

SETO sCO_2 Power Cycle Portfolio by Category

CATEGORY	PROJECT TITLE	PRIME
Turbomachinery	Compression System Design and Testing for sCO_2 CSP Operation	GE
	Development of an Integrally-Geared sCO_2 Compander	Southwest Research Institute
	Development of High Efficiency Expander and 1 MW Test Loop	Southwest Research Institute
	Physics-Based Reliability Models for sc-CO_2 Turbomachinery Components	GE
	Process Gas Lubricated Bearings in Oil-Free Drivetrains	GE
	High-Temperature Dry-Gas Seal Development and Testing	Southwest Research Institute
Materials	Lifetime Model Development for Supercritical CO_2 CSP Systems	Oak Ridge NL
	sCO_2 Corrosion and Compatibility with Materials	UW-Madison
Other Components	Development and Testing of a Switched-Bed Regenerator	UW-Madison
	sCO_2 Power Cycle with Integrated Thermochemical Energy Storage	Echogen Power Systems
	High-Efficiency Hybrid Dry Cooler System for sCO_2 Power Cycles	Southwest Research Institute
	Additively Manufactured sCO_2 Power Cycle Heat Exchangers for CSP	GE
Technoeconomics	Cycle Modeling, Integration with CSP, and Technoeconomics	NREL
Primary Heat Exchanger	High Flux Microchannel Direct sCO_2 Receiver	Oregon State U.
	High-Temperature Particle Heat Exchanger for sCO_2 Power Cycles	Sandia NL
	Various Molten Salt-to-sCO_2 Heat Exchangers	Purdue / UC Davis / Comprex
	Fluidized Beds for Effective Particle Thermal Energy Transport	Colorado School of Mines

Gen3 Topic 2 and Lab Support Awards

CATEGORY	PRIME	PROJECT TITLE	PI	AWARD
Liquid (2A)	**Hayward Tyler**	Development of High Temperature Molten Salt Pump Technology for Gen3	Benjamin Hardy	$2,000,000
	MIT	High Temperature Pumps and Valves for Molten Salt	Asegun Henry	$1,932,414
	Powdermet, Inc	High Toughness Cermets for Molten Salt Pumps	Joseph Hensel	$1,326,384
	MIT	Ceramic Castable Cement Tanks and Piping for Molten Salt	Asegun Henry	$1,771,798
Liquid (2B and Lab Support)	**Purdue**	Robust High Temperature Heat Exchangers	Kenneth Sandhage	$1,960,745
	Rensselear Polytechnic Institute	Development of In-Situ Corrosion Kinetics and Salt Property Measurements of salts and containment materials	Li (Emily) Liu	$1,799,892
	Savannah River NL	Full Loop Thermodynamic Corrosion Inhibition and Sensing in Molten Chloride	Brenda Garcia-Diaz	$1,000,000
	NREL	Molten Chloride Thermophysical Properties, Chemical Optimization, and Purification	Judith Vidal	$1,000,000
	Oak Ridge National Lab	Enabling High-Temperature Molten Salt CSP through the Facility to Alleviate Salt Technology Risks (FASTR)	Kevin Robb	$4,300,000
	Oak Ridge National Lab	Progression to Compatibility Evaluations in Flowing Molten Salts	Bruce Pint	$1,000,000
	Oak Ridge National Lab	Comparison of Protecting Layer Performance for Corrosion Inhibition in Molten Chloride Salts through Interfacial Studies at the Molecular Scale	Sheng Dai	$955,000

Gen3 Topic 2 and Lab Support Awards

CATEGORY	PRIME	PROJECT TITLE	PI	Award
Particle (2B and Lab Support)	**Georgia Institute of Technology**	Advanced Characterization of Particulate Flows for CSP Applications	Peter Loutzenhiser	$1,352,195
	U. of Tulsa	GEN3D – Experimental and Numerical Development of GEN3 Durability Life Models	Todd Otanicar	$1,515,687
	Sandia National Labs	Characterization and Mitigation of Radiative, Convective, and Particle Losses in High-Temperature Particle Receivers	Cliff Ho	$1,031,070
	Sandia National Labs	Quantifying thermophysical properties and durability of particles and materials for direct and indirect heat transfer mechanisms	Kevin Albrecht	$445,000
Gas (2A)	**Brayton Energy**	Development of Integrated Thermal Energy Storage Heat Exchangers for CSP Applications	Jim Nash	$1,181,603
	Mohawk Innovative Technology, Inc	Oil-Free, High Temperature Heat Transfer Fluid Circulator	Hooshang Heshmat	$1,258,629
Gas (Lab Support)	**Idaho National Lab**	Creep-fatigue behavior and damage accumulation of a candidate structural material for a CSP thermal receiver	Michael McMurtrey	$1,000,000
Agnostic (2B and Lab Support)	**Georgia Institute of Technology**	Thermophysical Property Measurements of Heat Transfer Media and Containment Materials	Shannon Yee	$1,966,440
	UC San Diego	Non-contact thermophysical characterization of solids and fluids for CSP	Renkun Chen	$1,180,000
	EPRI	Improving Economics of Gen3 CSP System Components Through Fabrication and Application of High Temperature Ni-Based Alloys	John Shingledecker	$1,499,901
	Sandia National Labs	Design and Implementation of a 1-3 MWth sCO2 Support Loop for Maturation of Molten Salt, Particulate, and Gas phase Thermal Storage Primary Heat Exchangers	Matthew Carlson	$3,600,000