Concentrating Solar-thermal Power

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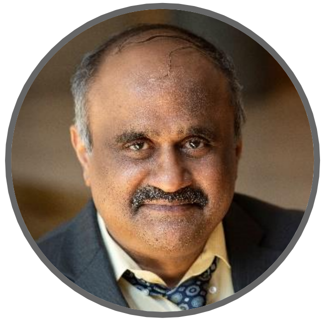
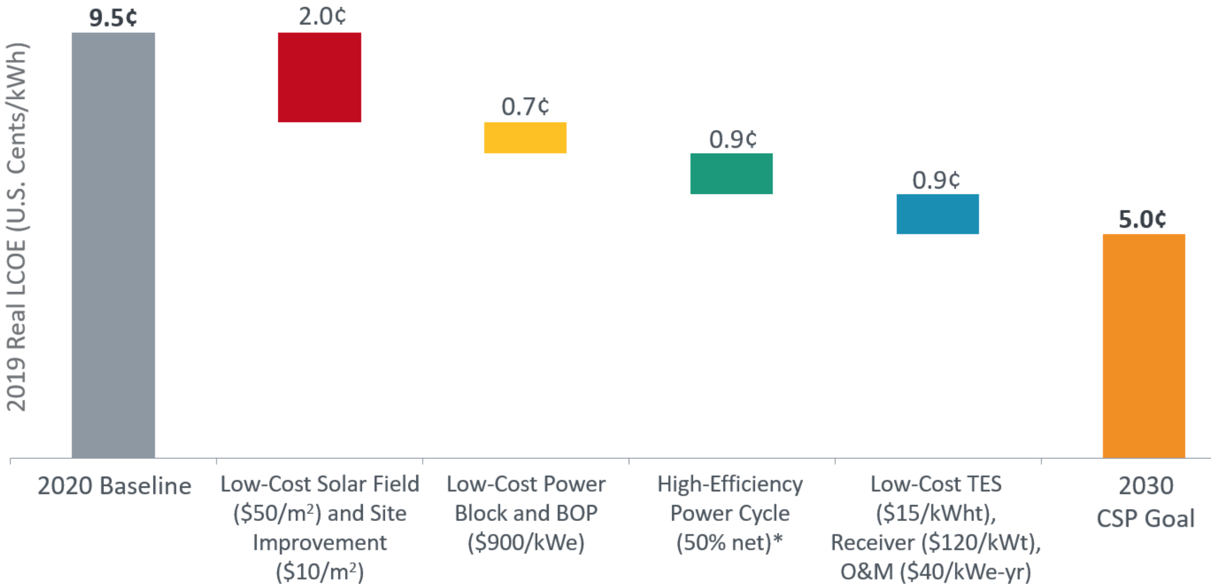
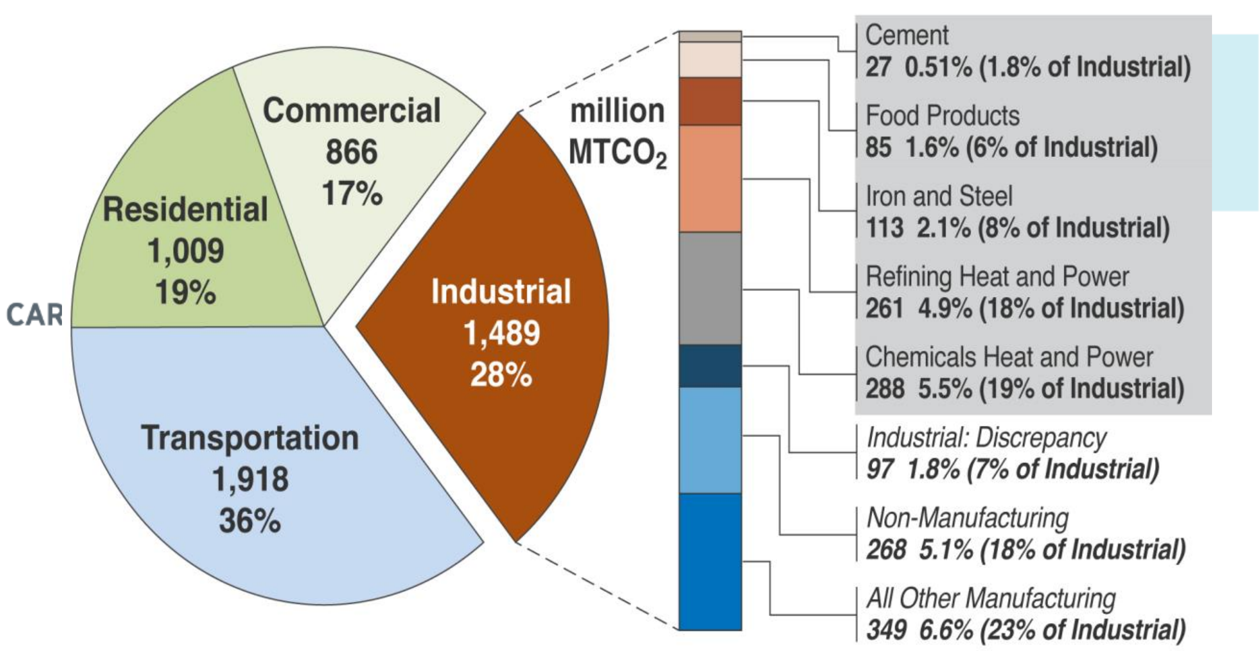


Rajgopal "Vijay" Vijaykumar

CSP Goals



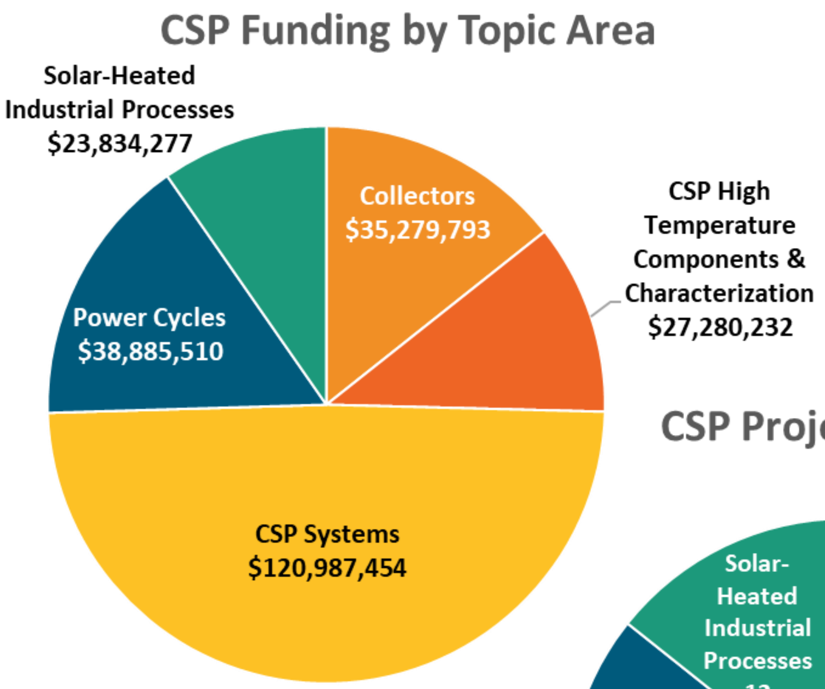
*Assumes a gross to net conversion factor of 0.9

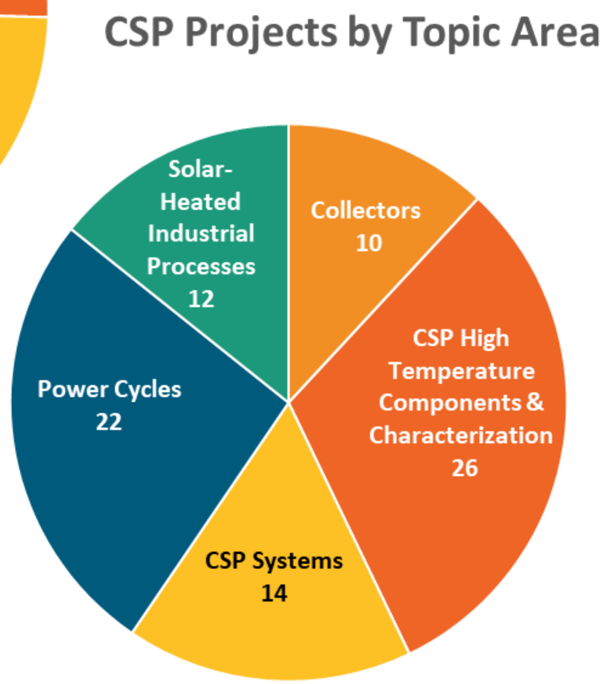


- Achieve LCOE goal through high efficiency power cycles operating at > 700 °C
- Reduce the levelized cost of heat, with thermal energy storage, to $0.02/kWhth, across a range of temperatures relevant to industrial processes

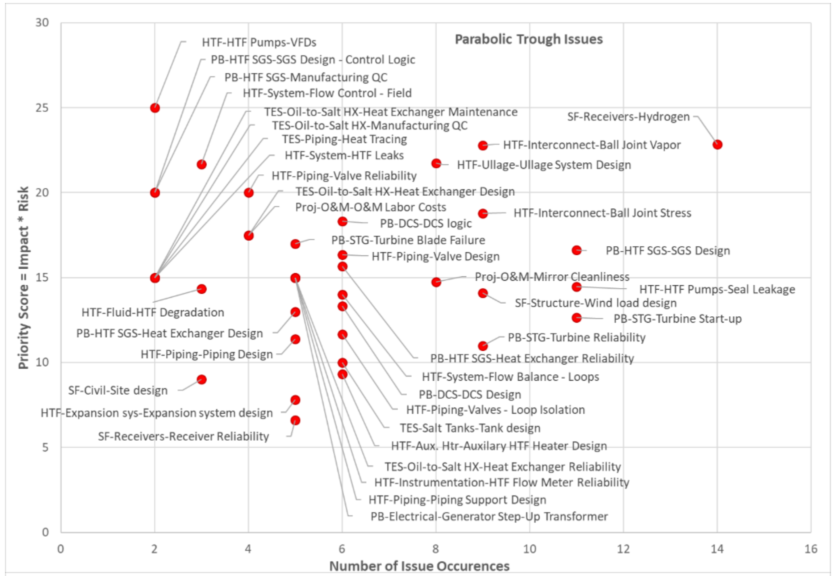
Active Funding Programs

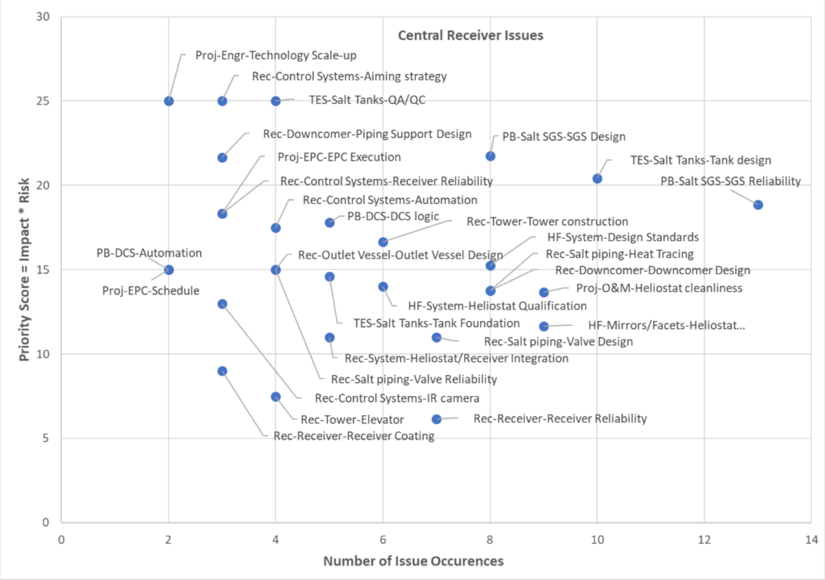
FOA/Year	Funding	Topics
SETO FY 2021 PV/CSP FOA	$30 million	Solar R&R
		Pumped TES
		PERFORM/REFORM
FY 2022-24 National Lab Call	$3 million	Lab Core Capabilities
	$25 million	Heliostat Consortium
	$25 million	Lab R&D
Solar Desal Prize Round 2 (2021)	$5 million	
SETO FY 2020 FOA	$39 million	Integrated TESTBED
Solar Desal Prize Round 1 (2020)	$10 million	
SETO FY 2019 FOA	$30 million	Firm TES
		Materials and Manufacturing
		Autonomous Collector Fields
FY 2019-21 National Lab Call	$3 million	Lab Core Capabilities
	$23 million	Lab R&D
Gen3 CSP FOA and Lab Call (2018)	$85 million	
Solar Desalination (2018)	$21 million	
SIPS (recurring)	~ $3 million per round	
SBIR (recurring)	*$XX million*	
Incubator (recurring)	*$XX million*	

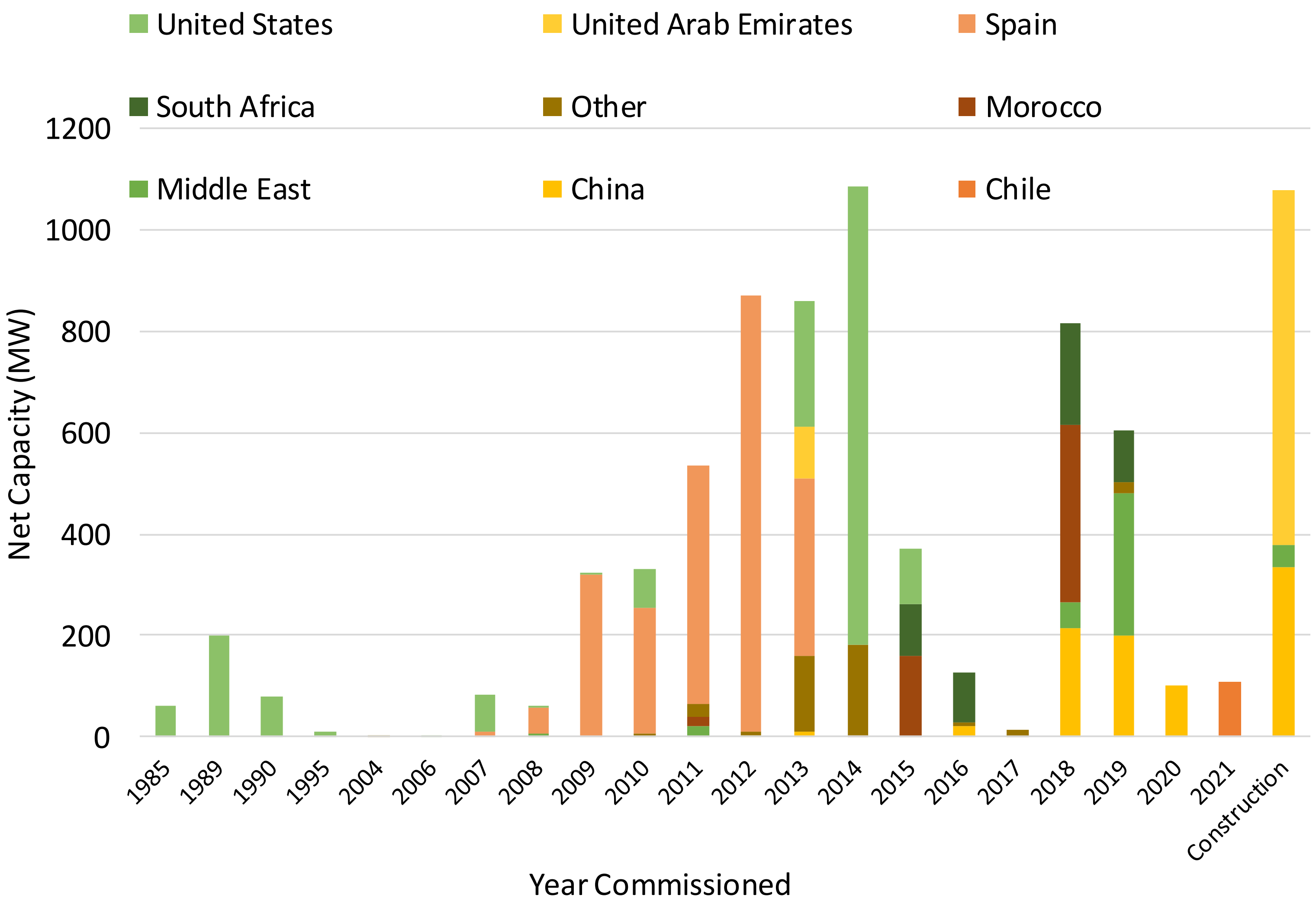




Documenting CSP Best Practices







Mehos, et al., 2020, NREL/TP-5500-75763

Process Enhancement and Refinement for Operations, Reliability, and Maintenance (CSP PERFORM)

Topic	Project / PI	Lead Organization
Steam Generator Reliability	**Improved O&M Reliability for CSP Plants through Application of Steam Generator Damage Mechanisms Theory & Practice;** *PI: Michael Caravaggio*	EPRI
Nitrate salt tanks and components	**Improved Design Standard for High Temperature Molten Nitrate Salt Tank Design;** *PI: Javier Alvarez*	IDOM
	Failure Analysis for Molten Salt Thermal Energy Storage Tanks for In-Service CSP Plants; *PI: Julian Osorio*	NREL
	Design Basis Document/Owners Technical Specification for Nitrate Salt Systems in CSP Projects; *PI: Bruce Kelly*	Solar Dynamics
Sensors	**Evaluation of High-Temperature Sensors for Molten Solar Salt Applications;** *PI: Jon Lubbers*	Sporian
Plant design optimization	**CSP Plant Optimization Study for the California Power Market;** *PI: Hank Price*	Solar Dynamics
Operator performance	**Performance Improvement in CSP Plant Operations;** *PI: Michael Wagner*	U. Wisconsin

New projects (beginning in 2022) are addressing highest priority issues in CSP commercial reliability

Collectors – Past and Current Efforts

SUNVAPOR
RENEWABLE PROCESS HEAT

Green Parabolic Trough Collector

Two design elements to achieve very low cost. 1) the use of a special grade of wood as the structural material, and the geometric arrangement of the structural members in a material-efficient typology.

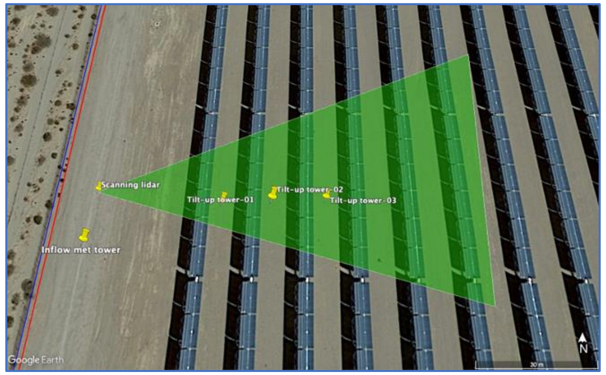
UFACET/NIO for Heliostats

UAV measurements of slope and canting errors in heliostats. Two approaches, using 1) a target heliostat and 2) the tower to determine errors.

NREL Transforming ENERGY
Sandia National Laboratories

Focused efforts have prioritized:

- Solar field capital cost reductions
  - Low-cost material replacements
  - Simplified heliostat and trough designs for faster assembly field deployment
- Improved metrology and characterization
  - Accelerate field calibration for improved energy output
  - Minimize operating costs through automated solar field analysis and controls



Wind Loading on Heliostats

Goal is to better understand the physics drivers underlying the wind-loading experienced by CSP collector and support structures. Includes characterization of the prevailing wind conditions and resulting operational loads and the ability to predict wind-loading in deep-array installations.

NREL Transforming ENERGY

Collectors – Heliostat Consortia

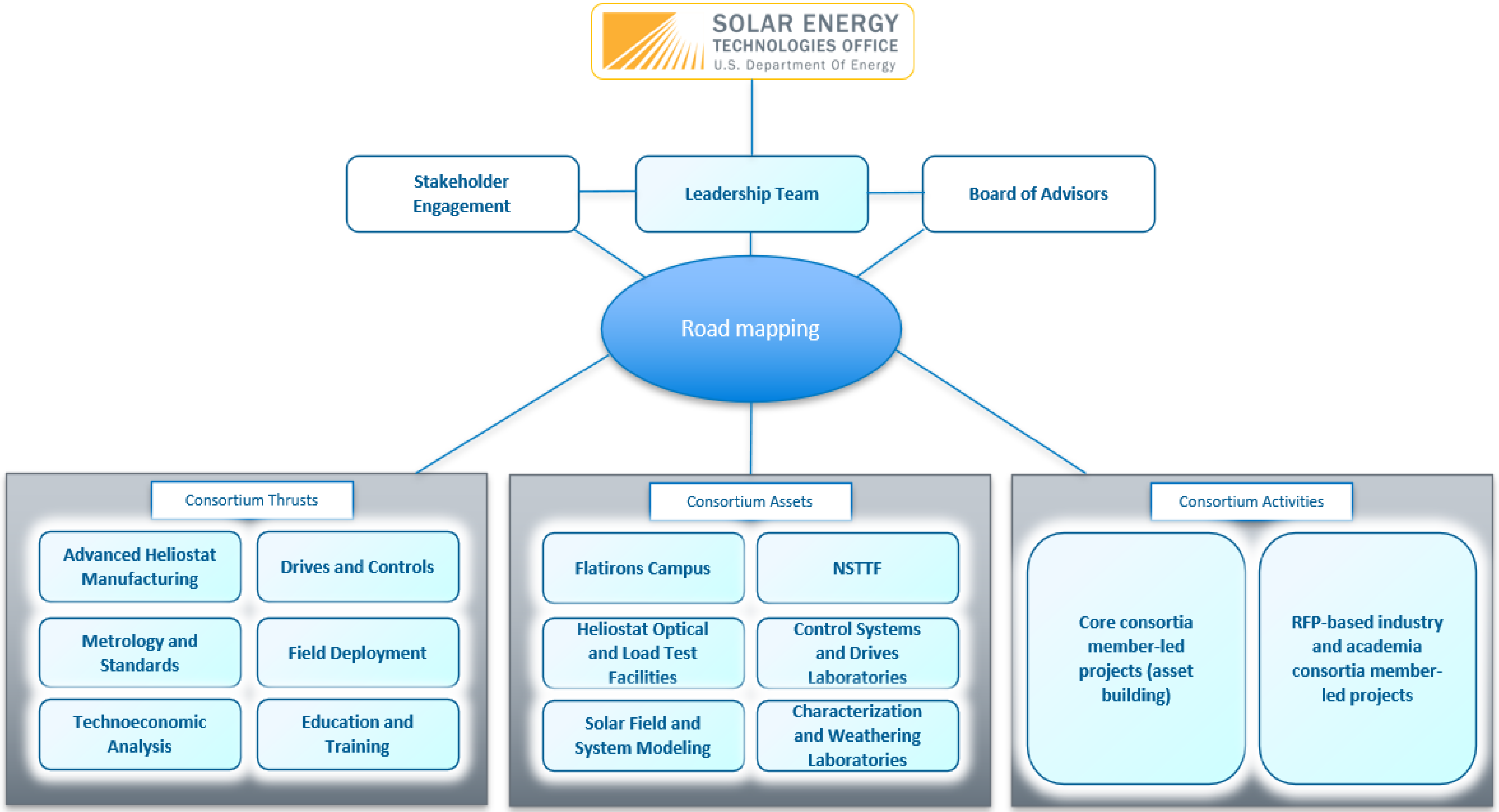
U.S. Department of Energy HelioCon Heliostat Consortium for Concentrating Solar-Thermal Power

Consortium Goals

- Accelerate innovation in heliostat development and reliability
- Develop National Laboratory core capabilities and infrastructure.
- Encourage collaboration between the CSP industry and US researchers

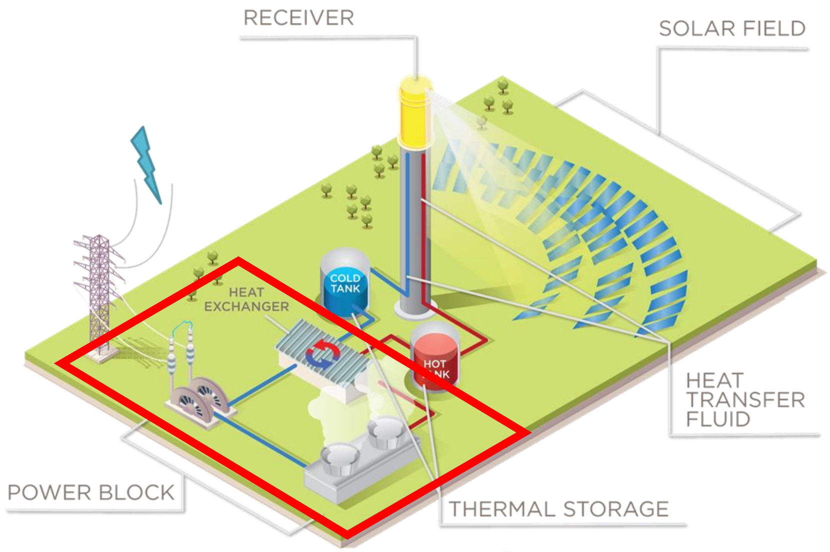
Consortium Structure

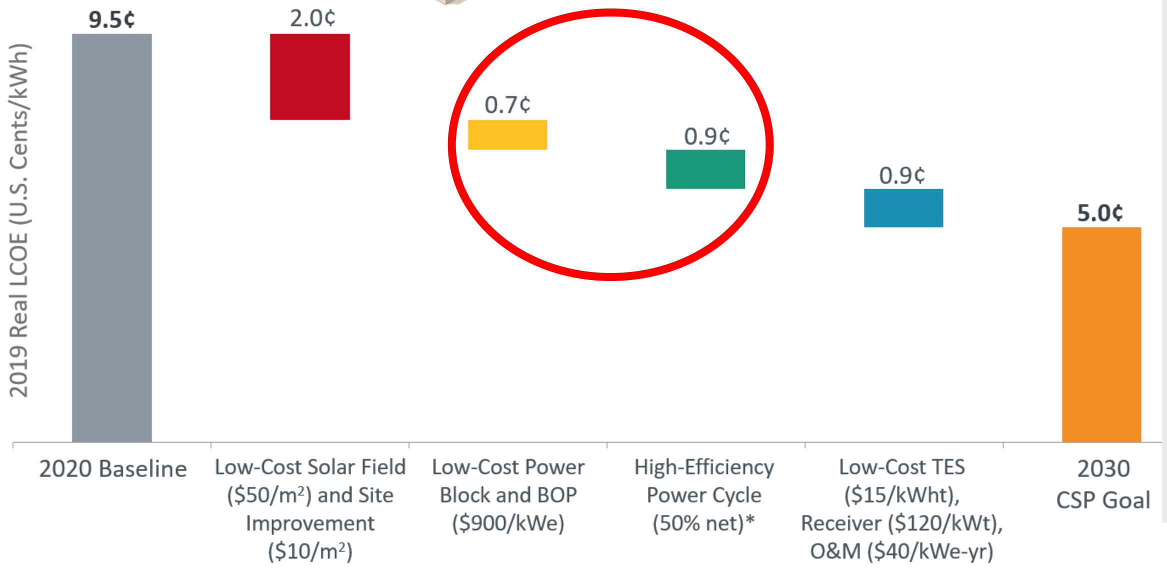
- 5-year, $25 million collaboration between NREL, Sandia, and ASTRI
- Periodic RFPs for collaboration between HelioCon and industry/academic researchers
- Emphasis on developing a diverse research and commercial workforce in CSP



NREL Transforming ENERGY | Sandia National Laboratories | ASTRI Australian Solar Thermal Research Institute

Advanced Power Cycles





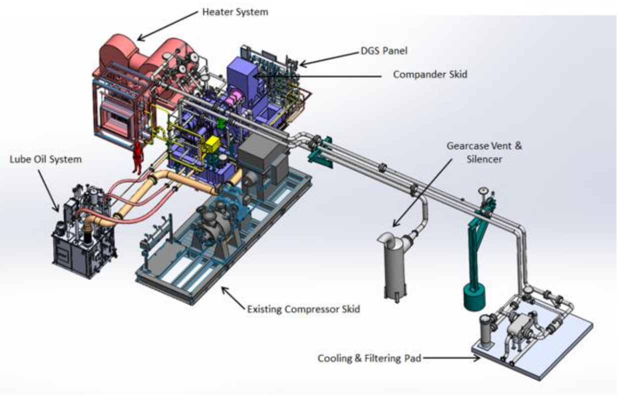
*Assumes a gross to net conversion factor of 0.9

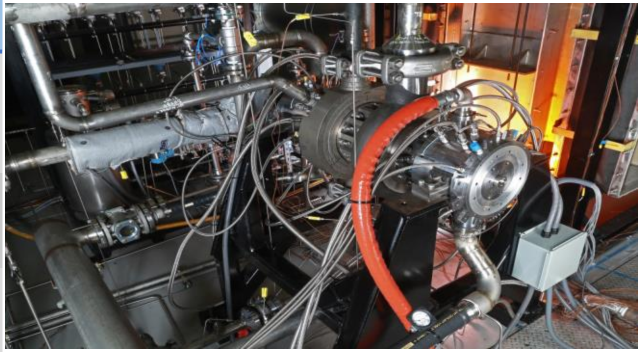
Programmatic Objectives

- Develop and demonstrate supercritical CO_2 power blocks consistent with > 50% net thermal-to-electric efficiency, including:
  - **Turbomachinery**
  - **Recuperators**
  - **Air cooling capability**
  - **Primary heat exchangers integrated with TES**
- Validate turbomachinery at MW_e scale ✓
- Support R&D on materials and manufacturing to **reduce cost to < $900 kW$_e$** for systems with **turbine inlet temperature > 700 ° C**
- Demonstrate commercially-relevant systems – with existing materials – at turbine inlet temperature approx. 600°C

sCO_2 Power Cycles – Completed and Ongoing Research

Component	Organization(s)	Status
Expander	Southwest Research Institute, GE Research	Successfully tested at 1 MW_e, 715°C for several hours
Compressor / Expander	Southwest Research Institute, Hanwha Power Systems	Successfully tested compressor and expander, at 1 MW_e to 715 °C; compressor inlet temperature to 36-37°C
Compressor	GE Research, Southwest Research Institute	Successfully tested compressor to inlet temperature 35°C
Seals	Southwest Research Institute, Eagle Burgmann	550-700°C dry gas seals being developed and tested
Bearings	GE Research	Gas bearing testing at large size
Air Cooler	Southwest Research Institute, Vacuum Process Engineering	Testing of MW_{th} sized air cooler



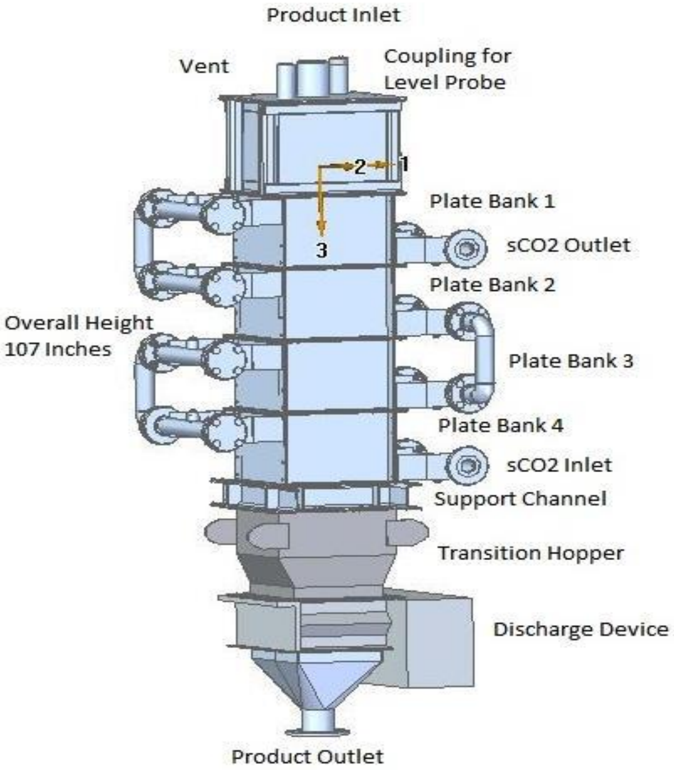


Remaining R&D challenges for power cycles > 700 °C :

- Low-cost manufacturing and fabrication for casing, recuperators, valves, air coolers
- Improved performance of seals and bearings to meet efficiency targets

Primary Heat Exchanger – Completed and Ongoing Research

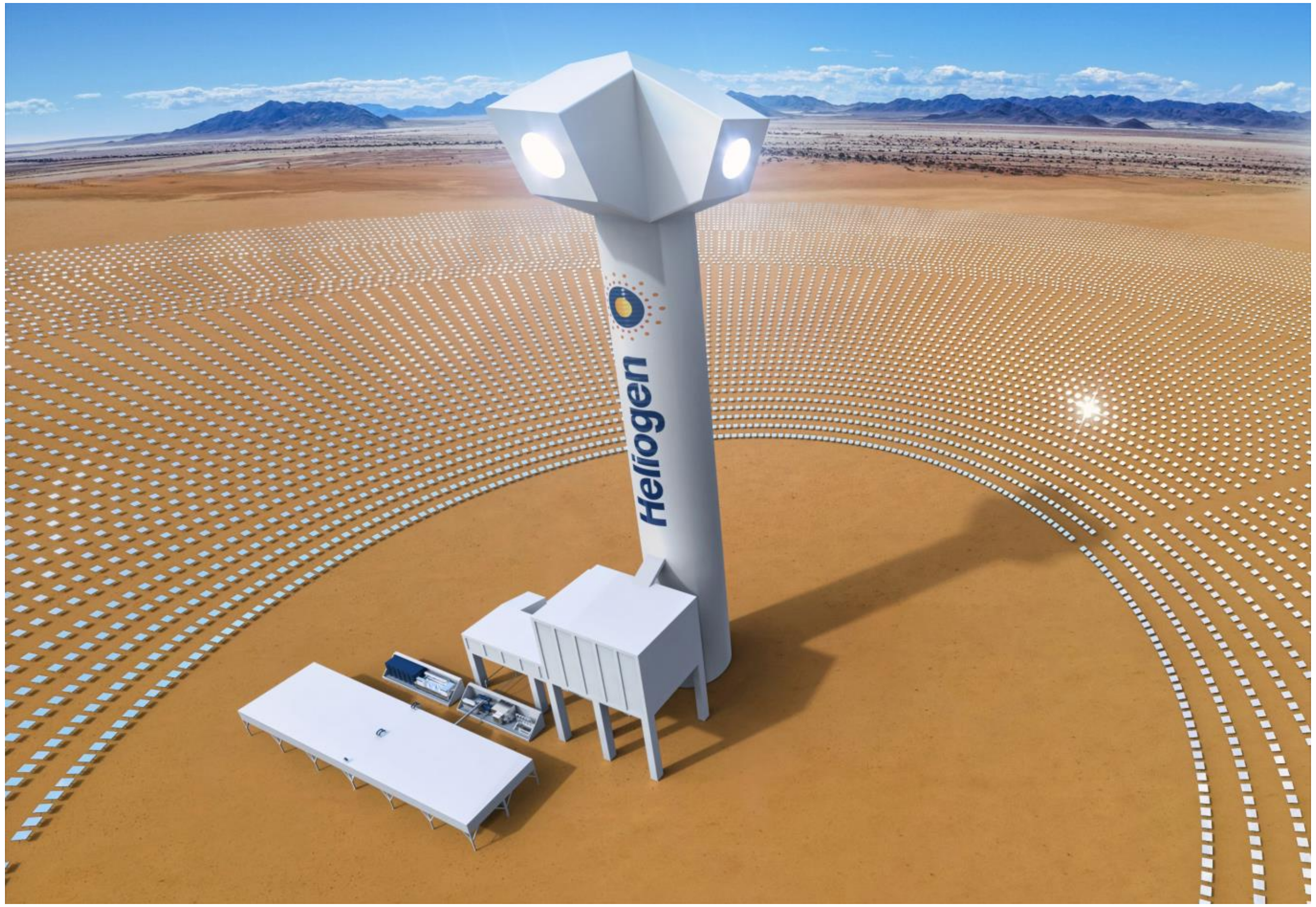
Description	Organizations	Status
100 kW_{th} Moving Bed	Sandia, Solex, VPE	Tested at 550-715°C for several hours; design improvements identified to overcome low heat transfer coefficients measured
20 kW_{th} Moving Bed	Sandia, Solex, VPE	Successfully tested stainless steel heat exchanger at 500°C to 200 W/m^2-K
≤50 kW_{th} Moving bed	Sandia, Solex, VPE	High alloy heat exchange procured for testing
100 kW_{th} Fluidized bed	Sandia, Babcock & Wilcox, TU-Wien	Build and test heat exchanger at SNL 100 kW_{th} facility
≤20 kW_{th} Moving Bed	Sandia, Argonne, Ex-one	SiC heat exchanger being built for 500-700°C application
14 MW_{th} Moving bed	Solex	Scaleup of large size stainless steel heat exchanger



Remaining R&D challenges for primary heat exchangers > 700 °C :

- Nickel alloy PHE cost exceeds 300 $/kWth; 200-400 W/m2.K heat transfer coeff. unproven
- No functional molten salt-sCO2 heat exchanger design for testing

Integrated TESTBED (*Th*ermal *E*nergy *St*orage and *B*rayton Cycle *E*quipment *D*emonstration)



TESTBED

- First-of-a-Kind sCO_2 facility integrated with TES; heat input from solar field
- 5 MW_e sCO_2 cycle at 600°C turbine inlet
- Heat input from 36,000 heliostats, 26.3 MW_{th}
- 3 receivers 13.4 MW_{th} each, supply heat for 8 hour, 213 MWh_{th} solid particle TES

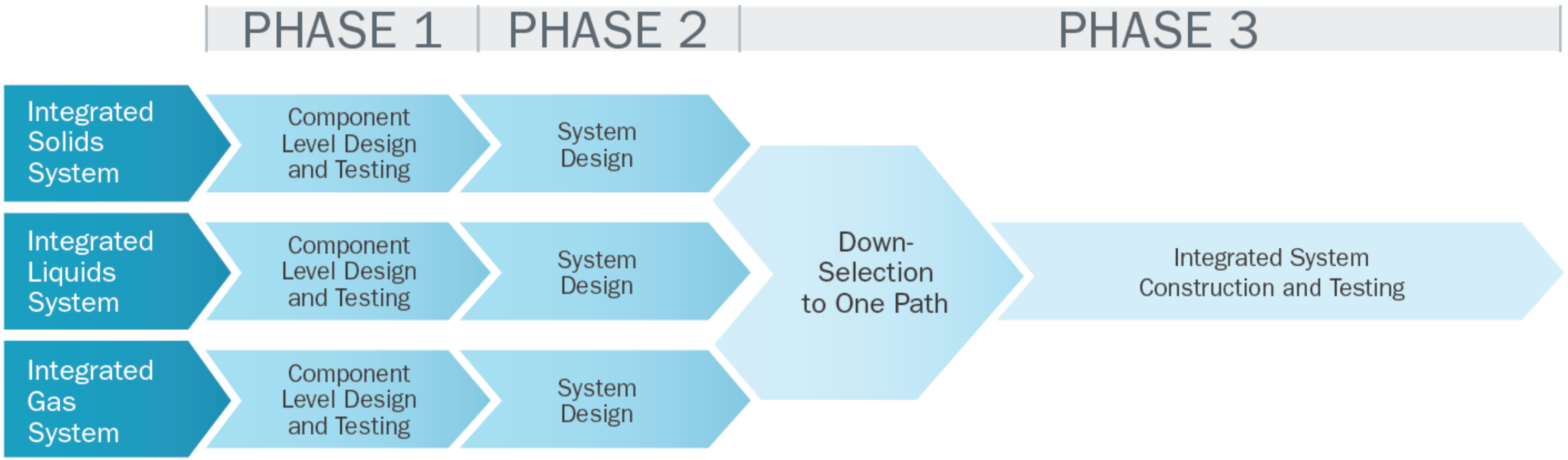
TESTING CAPABILITY

- Recompression Brayton Cycle (RCBC) operation
- RCBC control and integration with TES
- Turbomachinery durability and operation
- FOAK TES and heat exchanger

Gen3 CSP: Pathway Selection

TOPIC 1

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

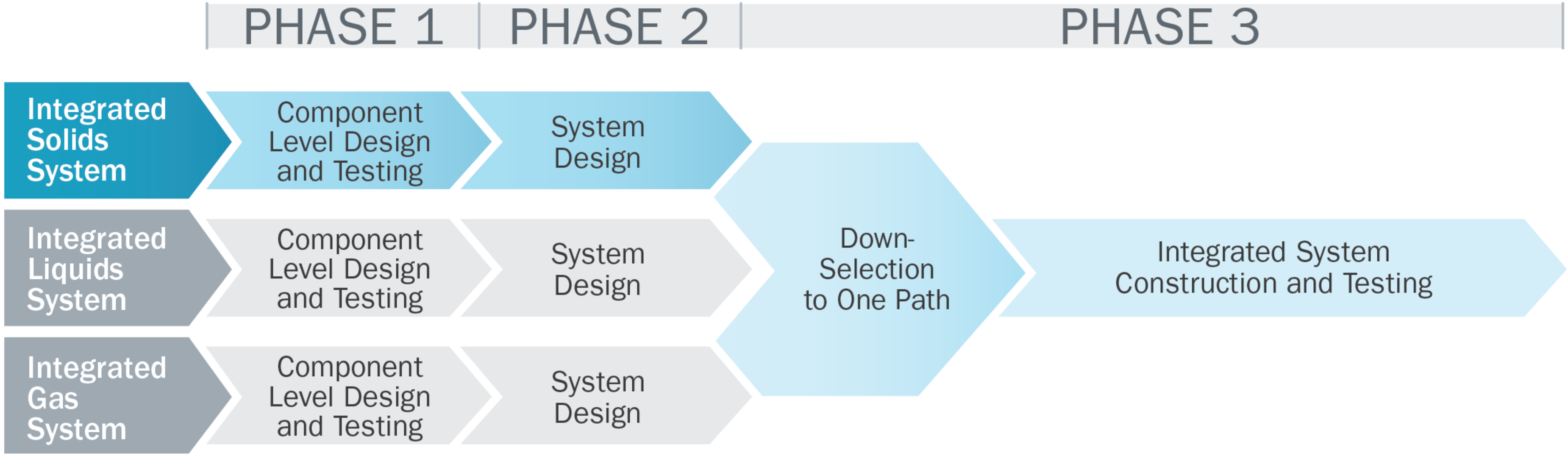


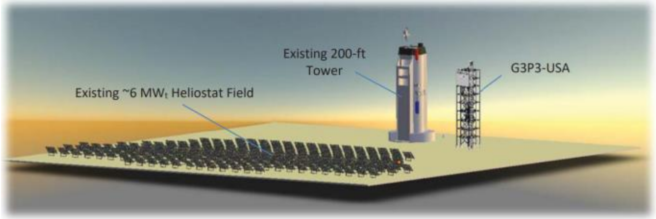
In March 2021, SETO announced that Sandia would receive $25 million to construct a MW-scale test facility at the National Solar Thermal Test Facility in Albuquerque, NM

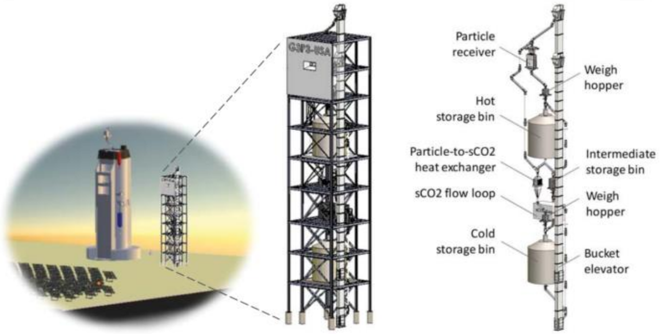
Gen3 CSP: Pathway Selection

TOPIC 1

- Sandia National Laboratories







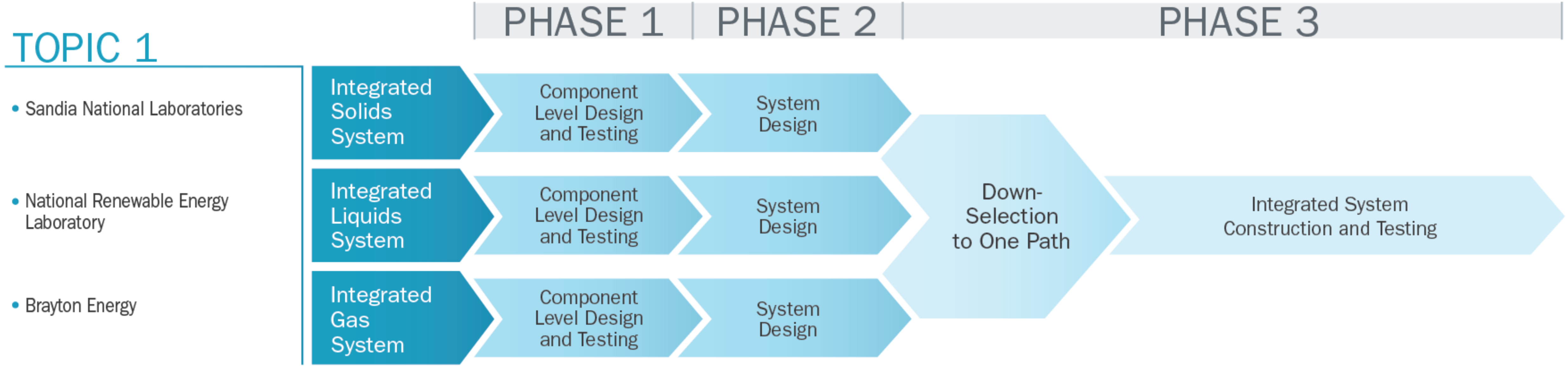
Strengths:

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

Remaining Gaps:

- Receiver optimization (also for controlled environments)
- Particle cost
- Demonstrations of flow control and particle handling at scale
- Increasing system ΔT

Gen3 CSP: Future Needs for Liquid and Gas Pathways



Liquid Pathway

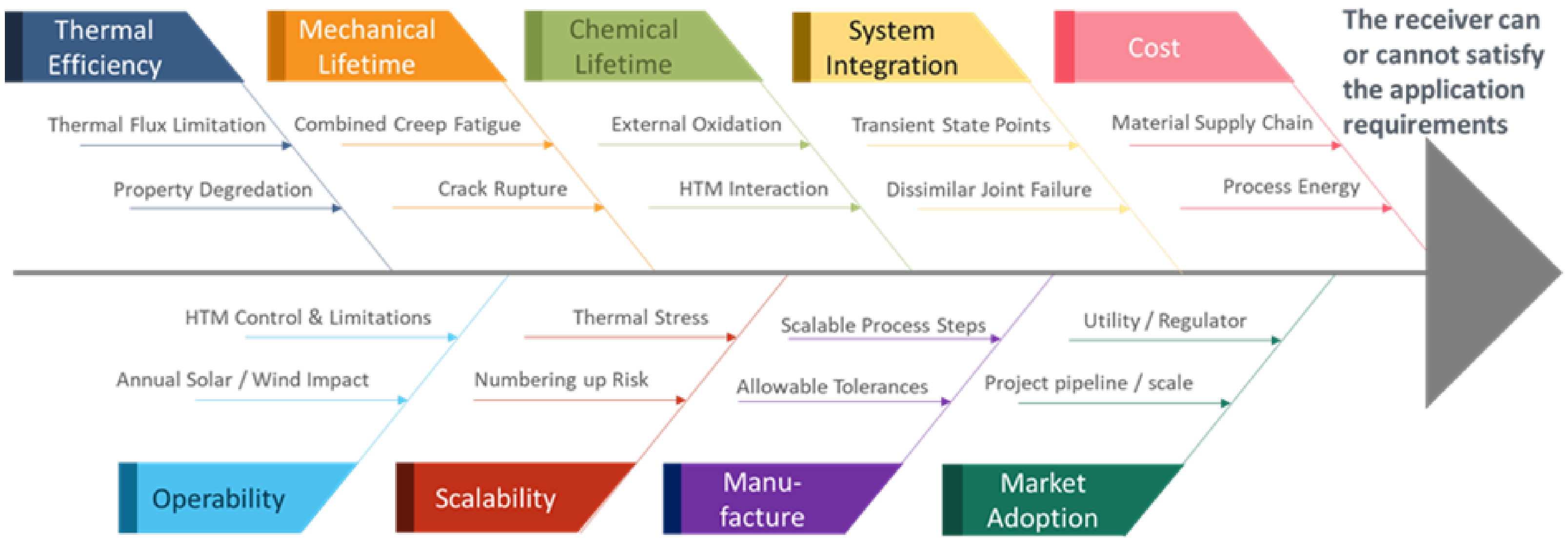
- Chloride salt is a promising low-cost TES media for multiple applications
- Validation of TES tank designs and chloride corrosion detection and controls
- Sodium receivers integrated with nitrate salt TES may lead to future adoption of chlorides

Gas Pathway

- More testing needed to validate reliability of receivers for high-flux applications
- Particle TES design, and particle-to-gas HXer could benefit a wide variety of future applications
- System designs needed to minimize pressure drop

CSP High Temperature Components: Receivers and Reactors

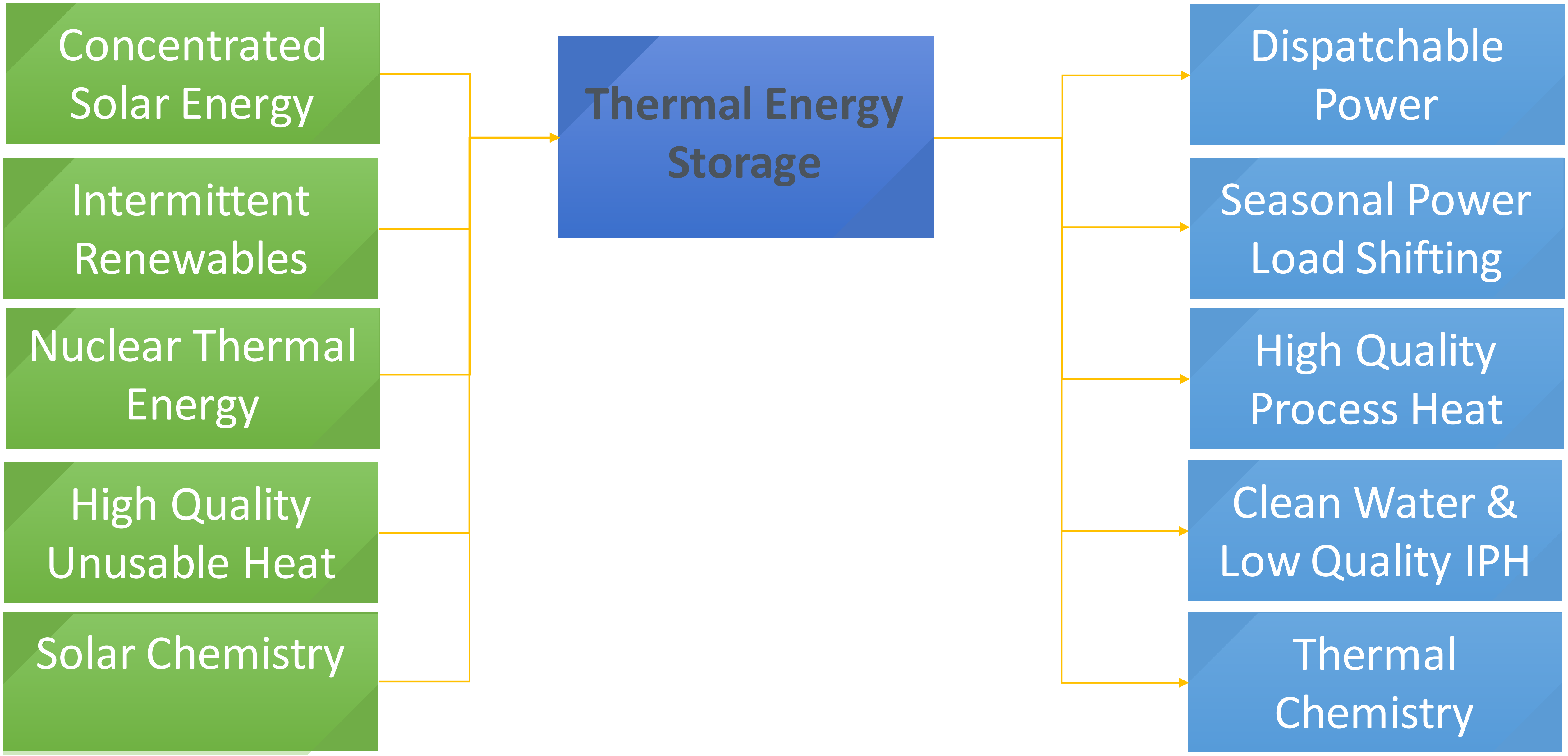
Programmatic Goal: Support solar receiver and reactor de-risking frameworks to enable new heat transfer media, higher temperature systems, and solar thermochemistry



Active Research

- Particle Based Receivers
- Solar Fuels
- Ammonia Synthesis
- 750°C power cycles
- High temperature materials
- Lifetime modeling tools
- MW_{th} testing campaigns

Thermal Energy Storage Enabled Systems



High Temperature Characterization, Validation, Monitoring

Intrinsic Properties in Lab Environment

- Thermal transport, material flow, castability
- Fatigue Limit, Yield Strength

Accelerated Lifetime Property Determination

- Performance property degradation
- Chemical and mechanical failure

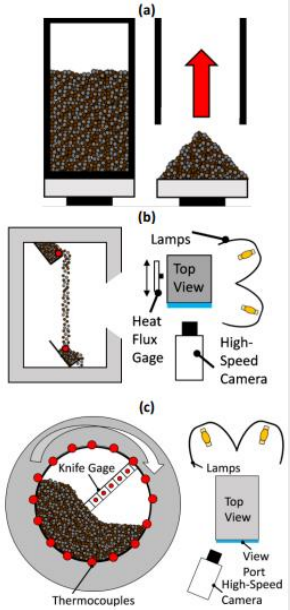
In Operation Local Property Identification

- Protype performance bankability
- Technology scale up de-risking

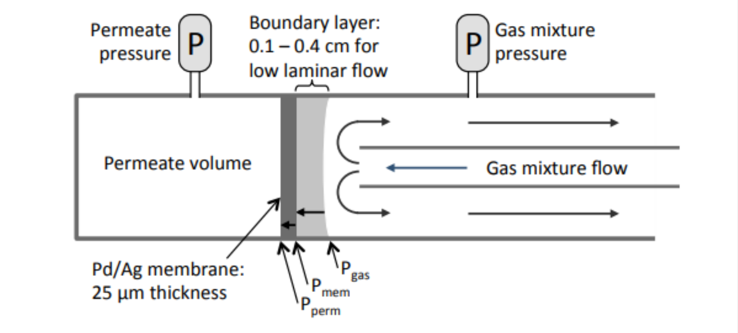
Commercial performance monitoring

- Control System Feedback and Operation
- Maintenance Planning

Andrew Schrader
University of Dayton

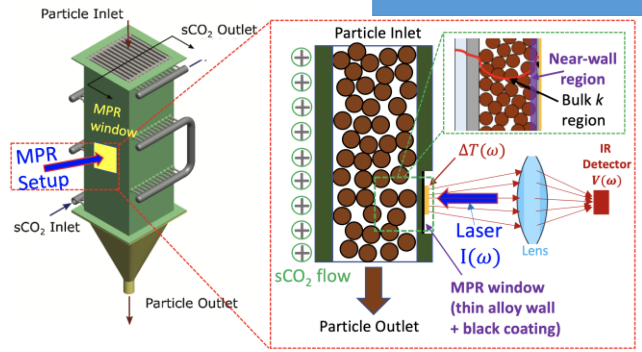


Greg Glatzmaier NREL

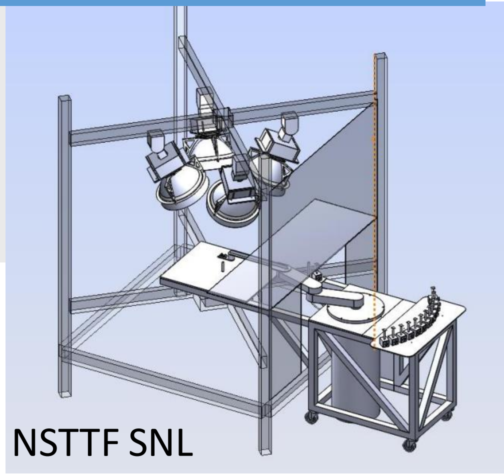


Challenges:

1. Harsh Environments
2. Nuanced Information
3. Data Reproducibility (FAIR Doctrine)
4. Environment Reproducibility
5. Long Term (Endurance) Testing



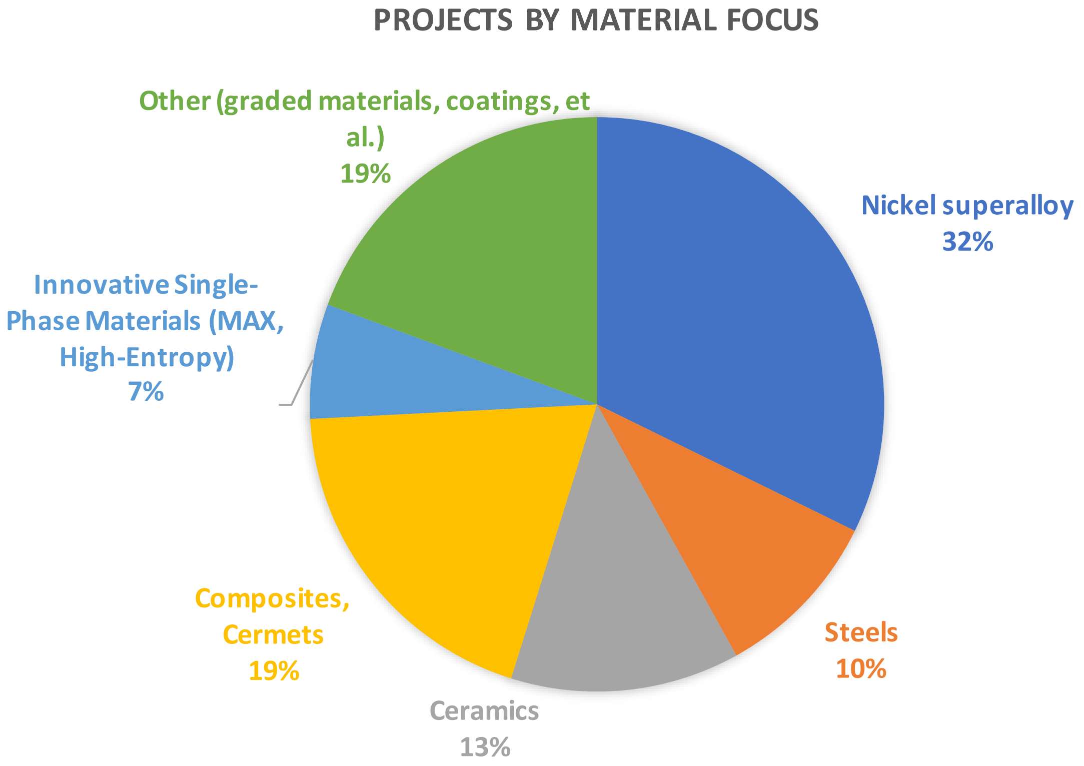
Renkun Chen UCSD

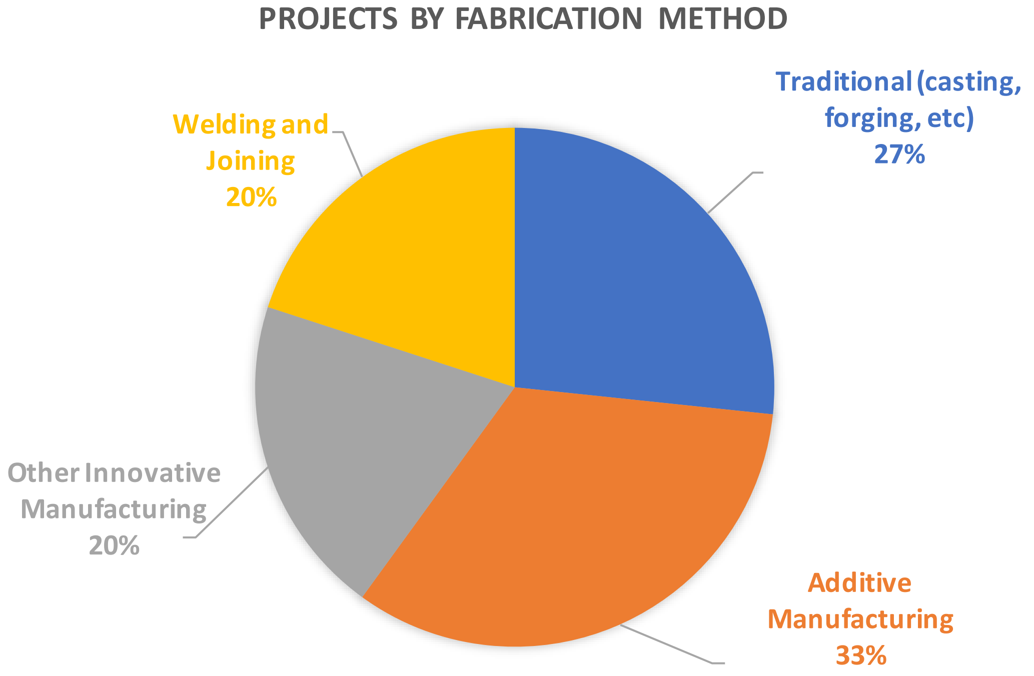


NSTTF SNL

CSP High Temperature Components and Characterization - Materials

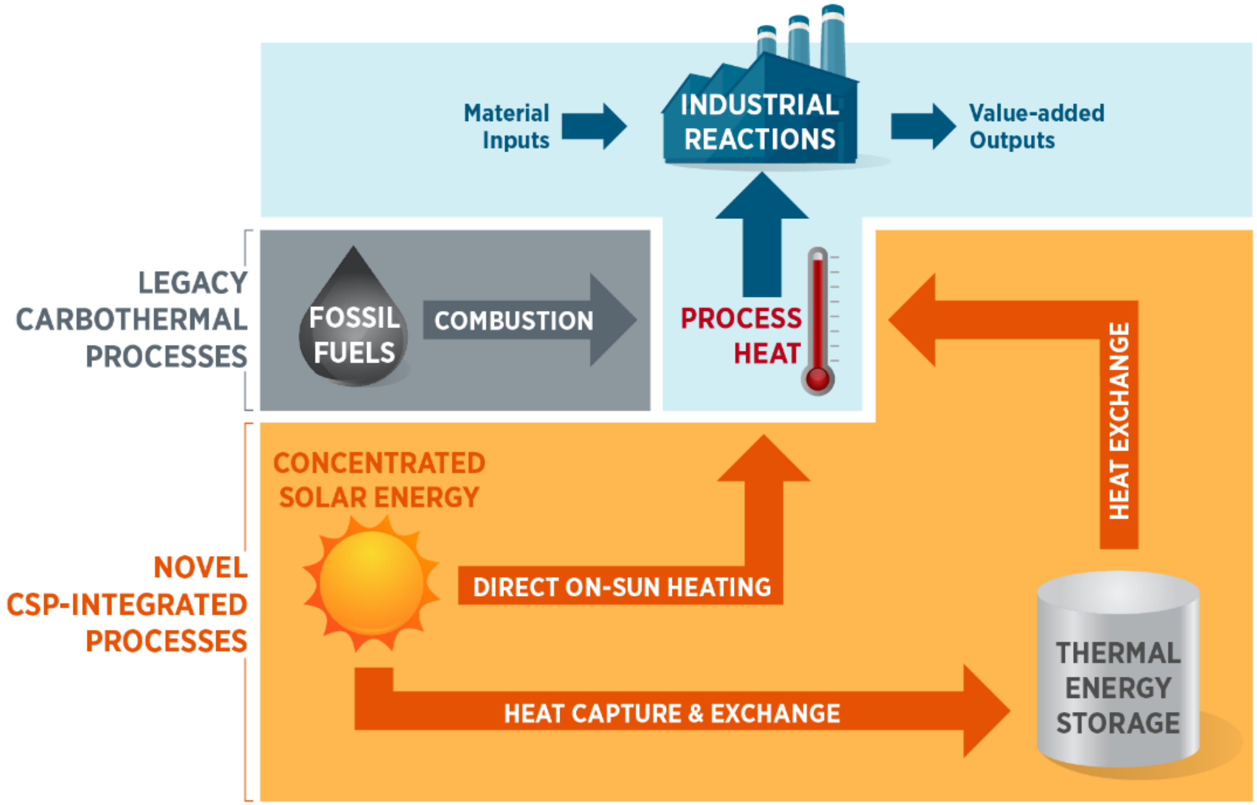
Materials see harsh service conditions that include temperature, pressure, chemical (salts, sCO_2), thermal cycling.





We seek continuous improvement in **thermo-mechanical properties** (Creep, Fatigue (low cycle), Creep-Fatigue, Tensile strength, Ultimate strength, Plastic deformation) and **chemical properties** (Corrosion, Erosion, (De)Carburization, Oxidation, liquid metal embrittlement)

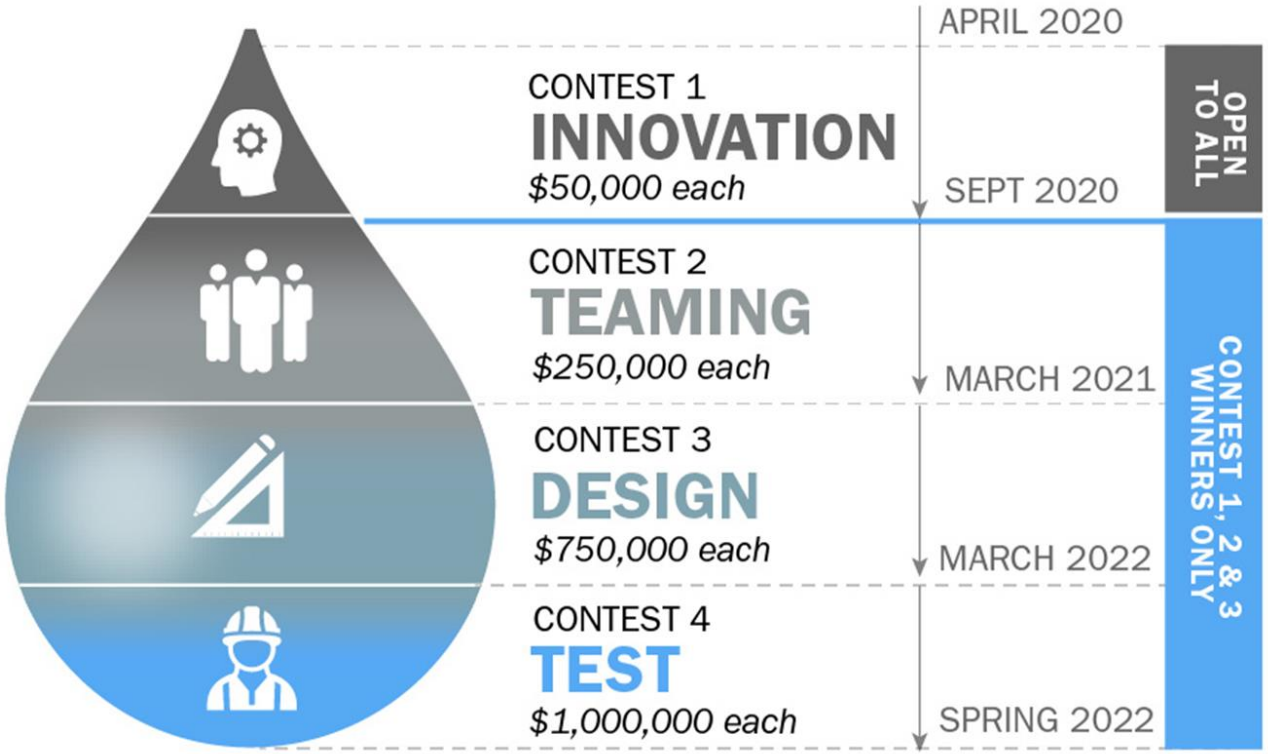
Solar Thermal for Decarbonization of Industrial Process Heat



Priority Research Areas

- Reduce the levelized cost of heat, **with thermal energy storage**, in temperature ranges of high priority to industrial processes
  - Roughly $0.02/kWh$_{th}$ would be competitive with natural gas
- Improve the **thermal efficiency** of solar-thermal-coupled processes
- Develop long-duration, thermochemical storage of solar energy (i.e. **solar fuels** and chemical commodities)

American Made Challenges: Solar Desalination Prize



ROUND 1

- Currently in the Design Contest
- 8 Competitors remain

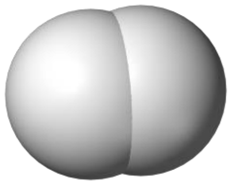
ROUND 2

- Currently in the Teaming Contest
- 12 Competitors remain

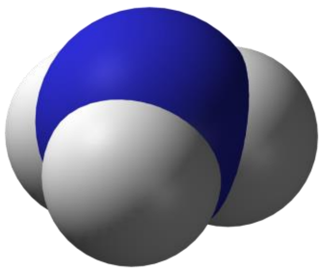
Accelerate commercialization of solar thermal desalination systems through successful demonstration of:

- Low-cost solar thermal collectors and thermal energy storage
- Innovative, highly efficient thermal desalination technologies

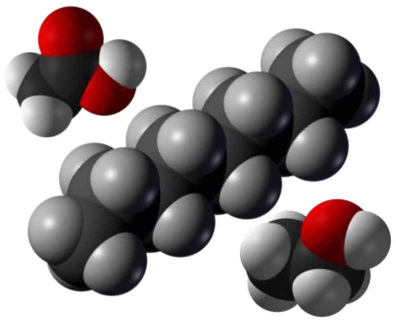
Solar Fuels for Energy Storage, Transport, Delivery



Hydrogen
- Amazing gravimetric energy density
- Chemical feedstock for NH_3, C_n fuels
- Multiple well-studied synthesis routes
- Abysmal volumetric energy density



Ammonia
- Acceptable energy density
- Plugs into legacy fertilizer infrastructure
- Potential hydrogen storage feedstock
- Unclear outlook as chemical fuel



Hydrocarbons
- High gravi/volumetric energy density
- Compatible w/ legacy infrastructure
- Requires CCS to reach net 0 emissions
- Product selectivity can be challenging

Funding Modalities for Targeted Impact

SIPS*

Seedling Projects

- Up to $400k over 18 months

Streamlined Application Process

- Reduced Application Steps, Documents, and Time

30 Projects Funded Since 2018

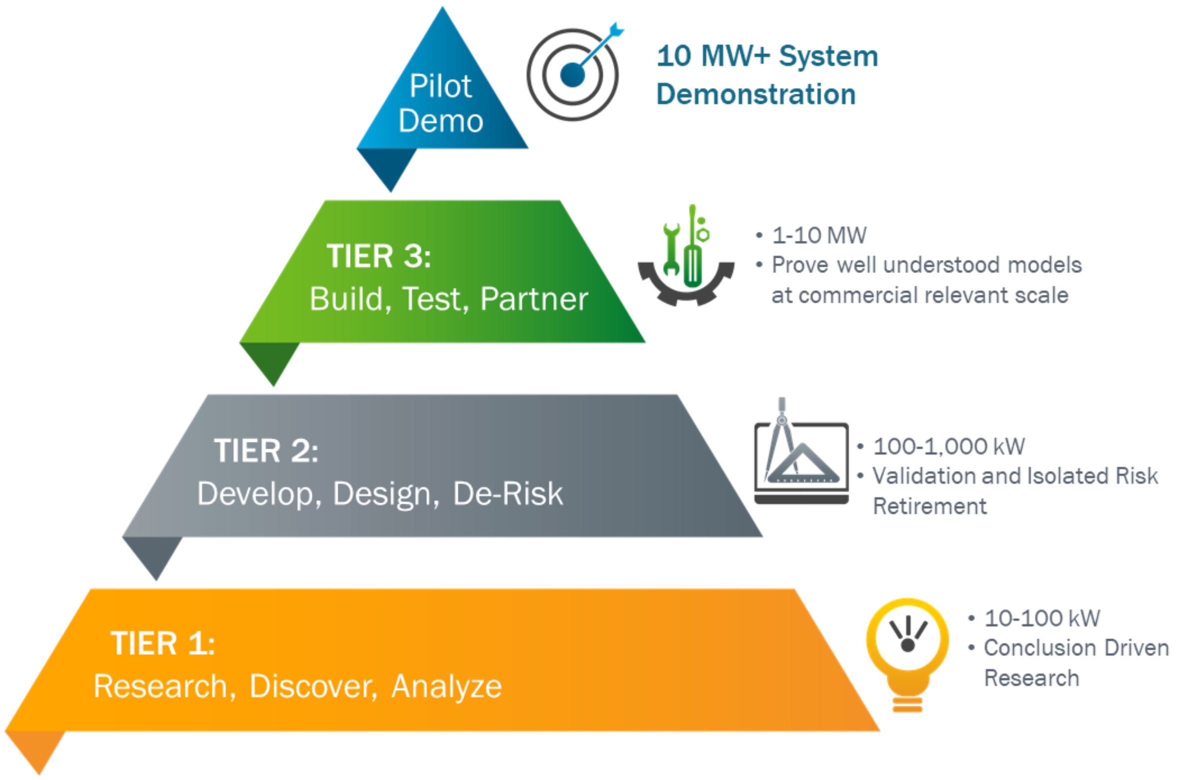
- Significantly increased the CSP R&D Community
- Increased Diversity of Institutions and Researchers

Strategic Importance

- Solutions for unique CSP frameworks, or
- Innovate to solve known programmatic gaps

*Small Innovative Projects in Solar

SOLAR** Tiers



**Scalable Outputs for Leveraging Advanced Research