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

Heating Up: Advances in Concentrating Solar-Thermal Power

Garrett Nilsen, Acting Director for the U.S. Department of Energy Solar Energy Technologies Office (SETO)
Avi Shultz, SETO Concentrating Solar-Thermal Power Program Manager

February 10, 2022

Welcome and Logistics

- This event is being recorded
- Slides, recording, and transcript will be available on energy.gov/seto-webinars
- Submit questions in the chat
- For technical difficulties, chat or email Jamal Ferguson (jamal.ferguson@ee.doe.gov)

Solar Energy Technologies Office

Our mission is to accelerate the development and application of technology to advance low-cost, reliable solar energy in the U.S.

To achieve this mission, solar energy must:

- Be **affordable** and **accessible** for all Americans
- Support the **reliability**, **resilience**, and **security** of the grid
- Create a sustainable industry that **supports jobs**, **manufacturing**, and the **circular economy** in a wide range of applications

Driving Toward Administration Decarbonization Goals

- **Reduce hardware and soft costs** of solar electricity **for all Americans** to enable an affordable carbon-free power sector by 2035.
- 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**.
- **Accelerate solar deployment and associated job growth** by opening new markets, reducing regulatory barriers, providing workforce training, and growing U.S. manufacturing.
- **Center energy justice** by reducing environmental impacts, removing barriers to equitable solar access, and supporting a diverse and inclusive workforce.
- **Support a decarbonized industrial sector** with advanced concentrating solar-thermal technologies and develop affordable renewable fuels produced by solar energy.

Solar Energy Technologies Office Leadership Team

Becca Jones-Albertus
Director (on detail to Advanced Manufacturing Office)

Garrett Nilsen
Acting Director

Paul Basore
Chief Scientist

Markus Beck
Manufacturing and Competitiveness Program Manager

Michele Boyd
Strategic Analysis and Institutional Support Program Manager

Sheila Moynihan
Operations Supervisor

Avi Shultz
Concentrating Solar-Thermal Power Program Manager

Nicole Steele
Workforce and Equitable Access Program Manager

Lenny Tinker
Photovoltaics Program Manager

Guohui Yuan
Systems Integration Program Manager

SETO Research Areas

PHOTOVOLTAICS

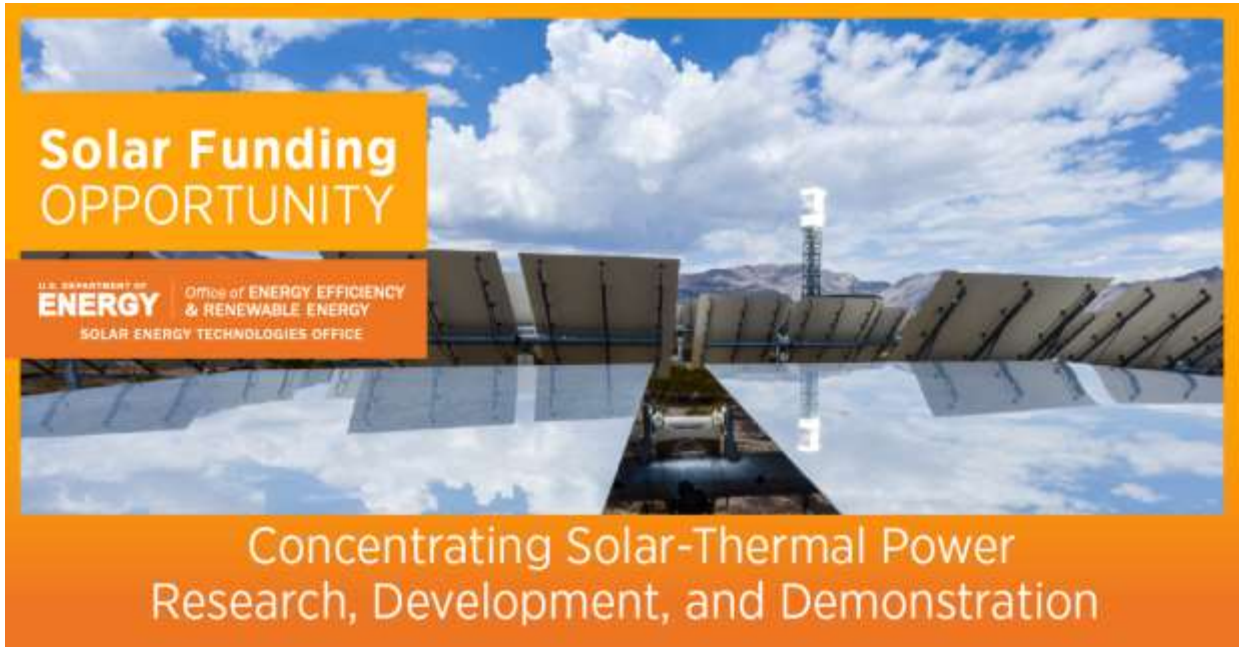
CONCENTRATING SOLAR-THERMAL

BALANCE OF SYSTEMS/
SOFT COST REDUCTION

SYSTEMS INTEGRATION

MANUFACTURING AND
COMPETITIVENESS

New Funding for Concentrating Solar-Thermal Power (CSP) and Photovoltaics



$25M for 8-15 projects that develop:

- CSP for carbon-free industrial processes
- High-efficiency CSP plant designs with low-cost thermal storage

Concept paper deadline: March 16, 5:00 p.m. ET

Info webinar: February 24, 2:00 p.m. ET

$5M for 15-23 seedling projects in photovoltaics and concentrating solar-thermal power that accelerate large-scale development and deployment of solar technology

Letter of intent deadline: February 28, 5:00 p.m. ET

Recent Announcements and Achievements

SETO released the "Solar Power in Your Community" guidebook to help local governments unlock benefits of increased solar deployment

SolarAPP+ (Solar Automated Permit Processing Plus) released pilot results:

- Reduced average permit review time to <1 day
- Enabled projects to be installed and inspected 12 days faster
- Saved communities 2,000+ hours of staff time

The National Community Solar Partnership held its second annual summit

- Discussed 2025 target of 5 million households powered by community solar, $1B energy bill savings
- Energy Secretary Jennifer Granholm announced a new States Collaborative, the Credit Ready Solar Initiative, and increased funding for technical assistance

SolSmart announced progress towards goal of 60 new SolSmart-designated communities in 6 months

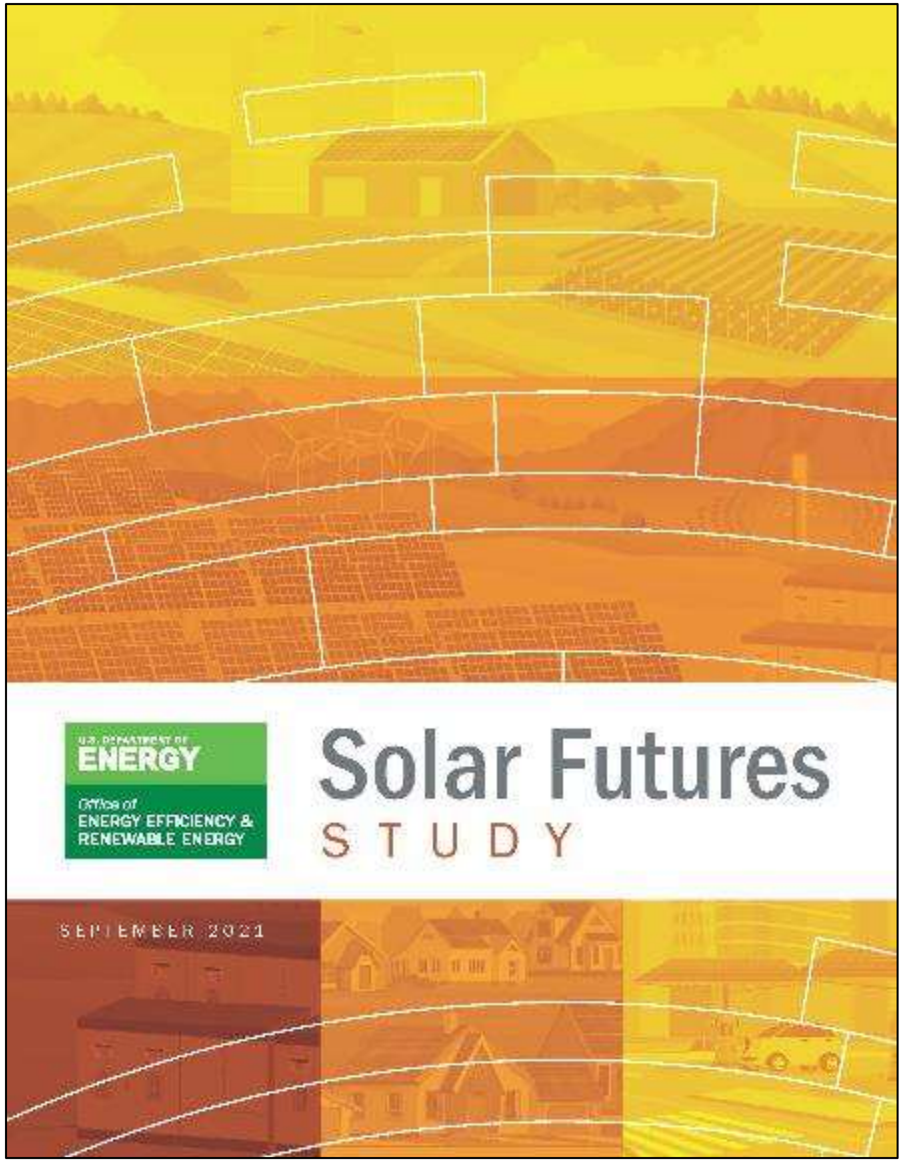
Study Overview

PURPOSE

- Comprehensive review of the potential role of *solar* in decarbonizing the electricity grid by 2035 and the energy system by 2050.
  - Addresses other large trends and activities across the U.S. economy that are necessary to achieve a zero-carbon energy system.
  - Builds analytical foundations to guide the next decade of solar research.

SCOPE

- Chapters cover future scenarios, technology advances, equity, grid integration, cross-sector interactions, supply chain, and environmental impacts.



Solar Futures Study: Key Results

1 **Deploy, deploy, deploy.** We must install an average of 30 GW of solar capacity per year between now and 2025 and 60 GW per year from 2025-2030. (In 2020 the U.S. installed 15 GW.)

- 1,000 GW of solar meets 40% of electric demand in 2035, 1,600 GW meets 45% in 2050.
- We must reshape workforce development, supply chains, siting and permitting, and regulation.
- Major growth in wind and storage are also required.

2 **With continued technological advances, electricity prices do not increase through 2035.** This includes solar, wind, energy storage, and other technologies.

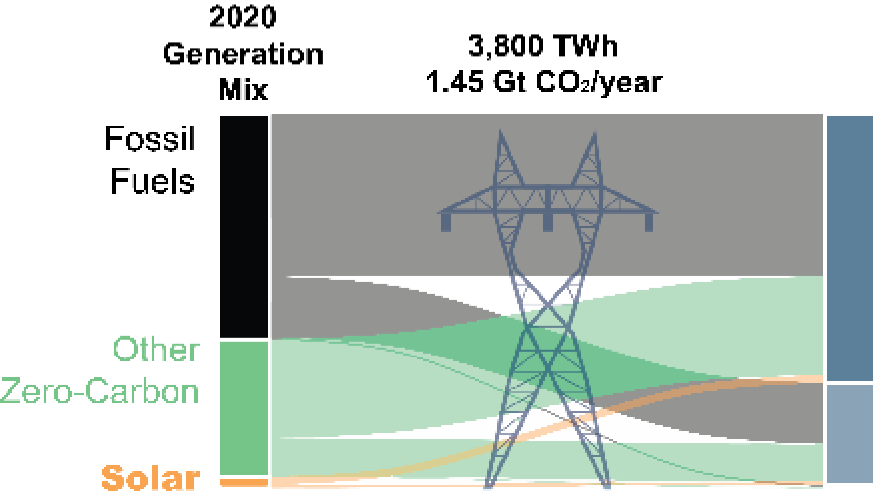
3 **The grid will be reliable and resilient.** Storage, transmission, and flexibility in load and generation are key.

4 **Expanding clean electricity supply yields deeper decarbonization.** Electrifying buildings, transportation, and industry reduces carbon emissions.

5 **Policy changes are necessary**. Limits on carbon emissions and/or clean energy incentives.

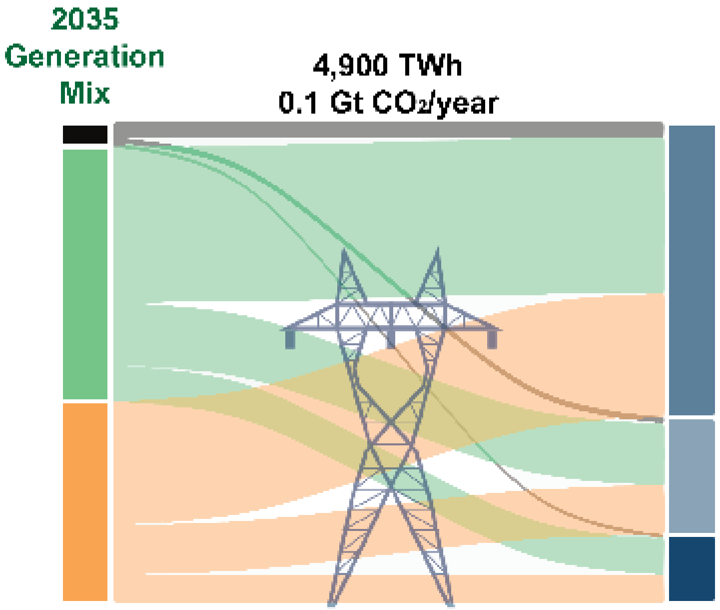
U.S. Energy Mix 2020-2050

The U.S. Electric Grid in 2020



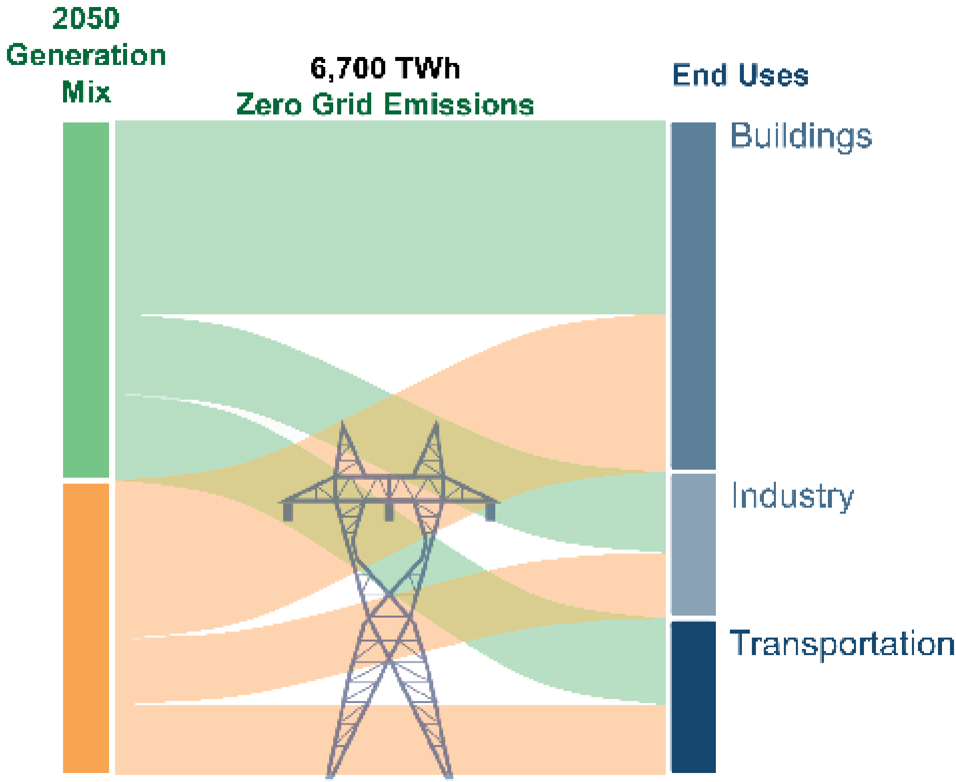
Solar: 3% of electricity demand, 80 gigawatts AC installed

95% Decarbonized Grid in 2035



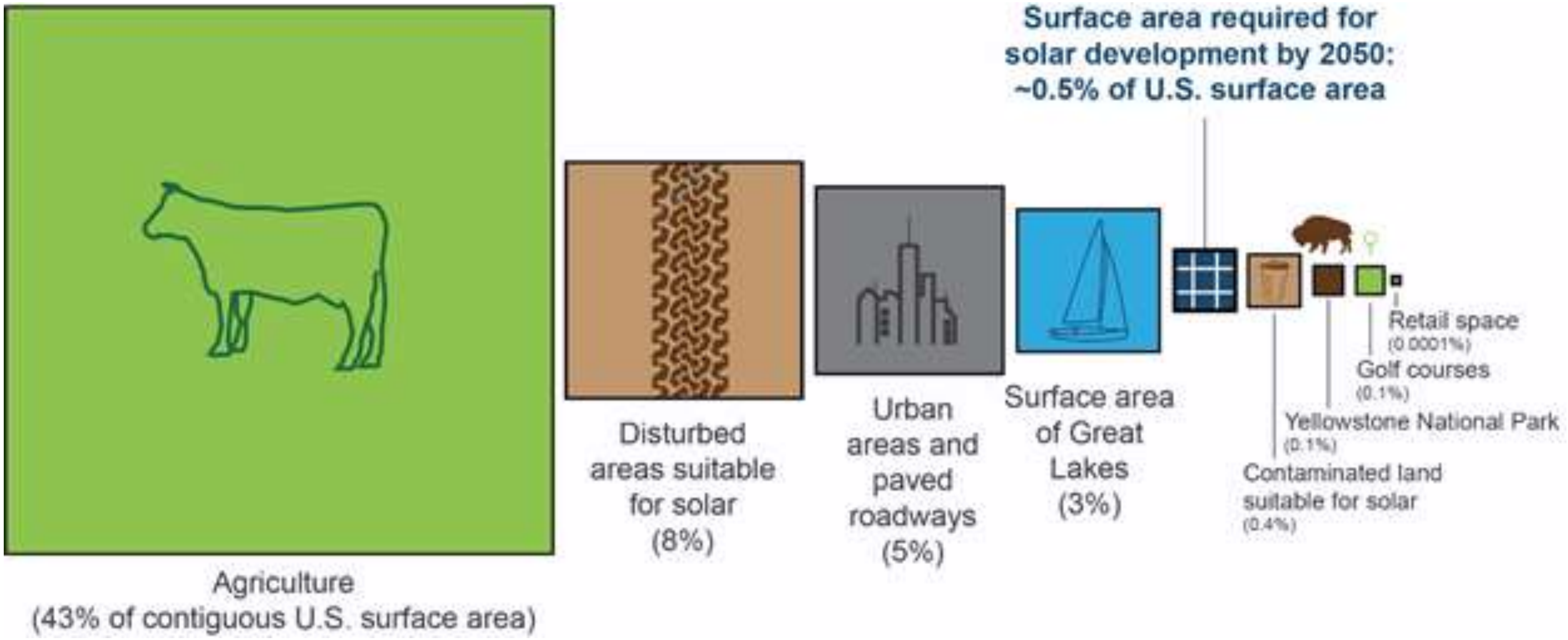
Solar: 40% of electricity demand, 1,000 gigawatts installed

Decarbonized Grid in 2050



Solar: 45% of electricity demand, 1,600 gigawatts installed
3,000 GW in decarbonized energy system

How much land will be required to achieve the scenarios?



Stay Connected with SETO

SETO is seeking project reviewers!

- Find out how to express your interest and more details on areas of expertise at **bit.ly/seto-reviewer**

Find out about new funding as soon as it's released

- Sign up for our Funding Notices mailing list at **bit.ly/eere-funding**

Congratulations to our newest SETO awardees!

- Fiscal Year 2021 Photovoltaics and Concentrating Solar-Thermal Power
- Connected Communities
- American-Made Solar Prize Round 4 Winners
- American-Made Solar Prize Round 5 Quarterfinalists

Concentrating Solar-Thermal Power (CSP)

Dr. Avi Shultz, Program Manager

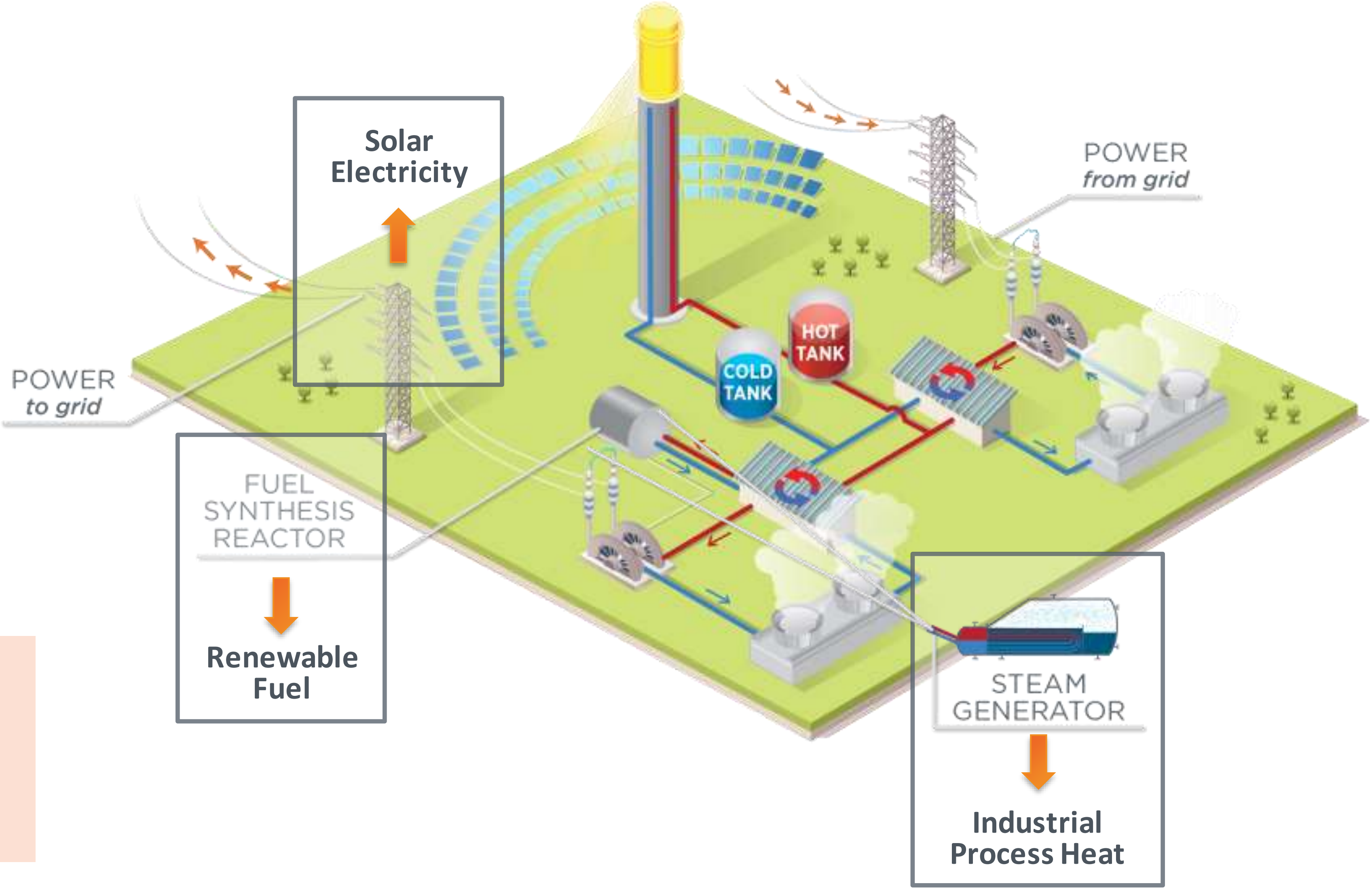
Oil-Based Troughs with steam rankine cycle (390 °C)

↓

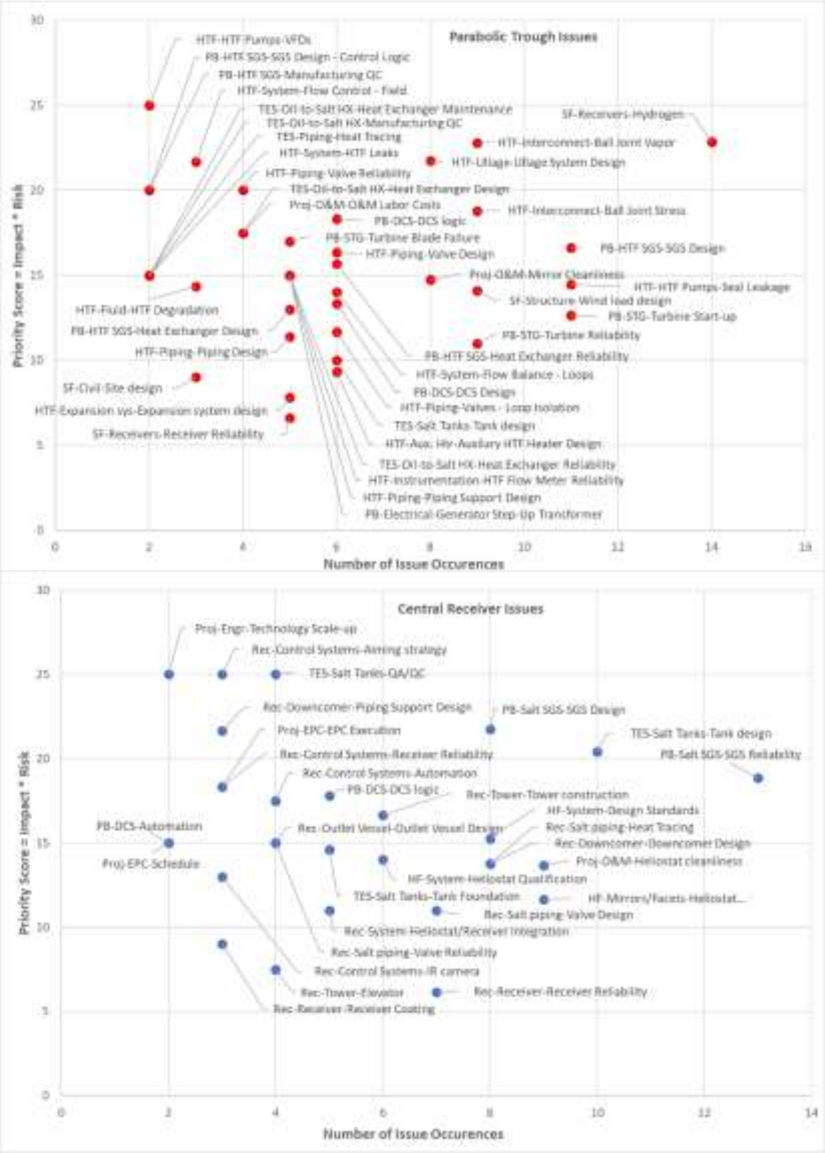
Molten Salt Towers with steam rankine cycle (565 °C)

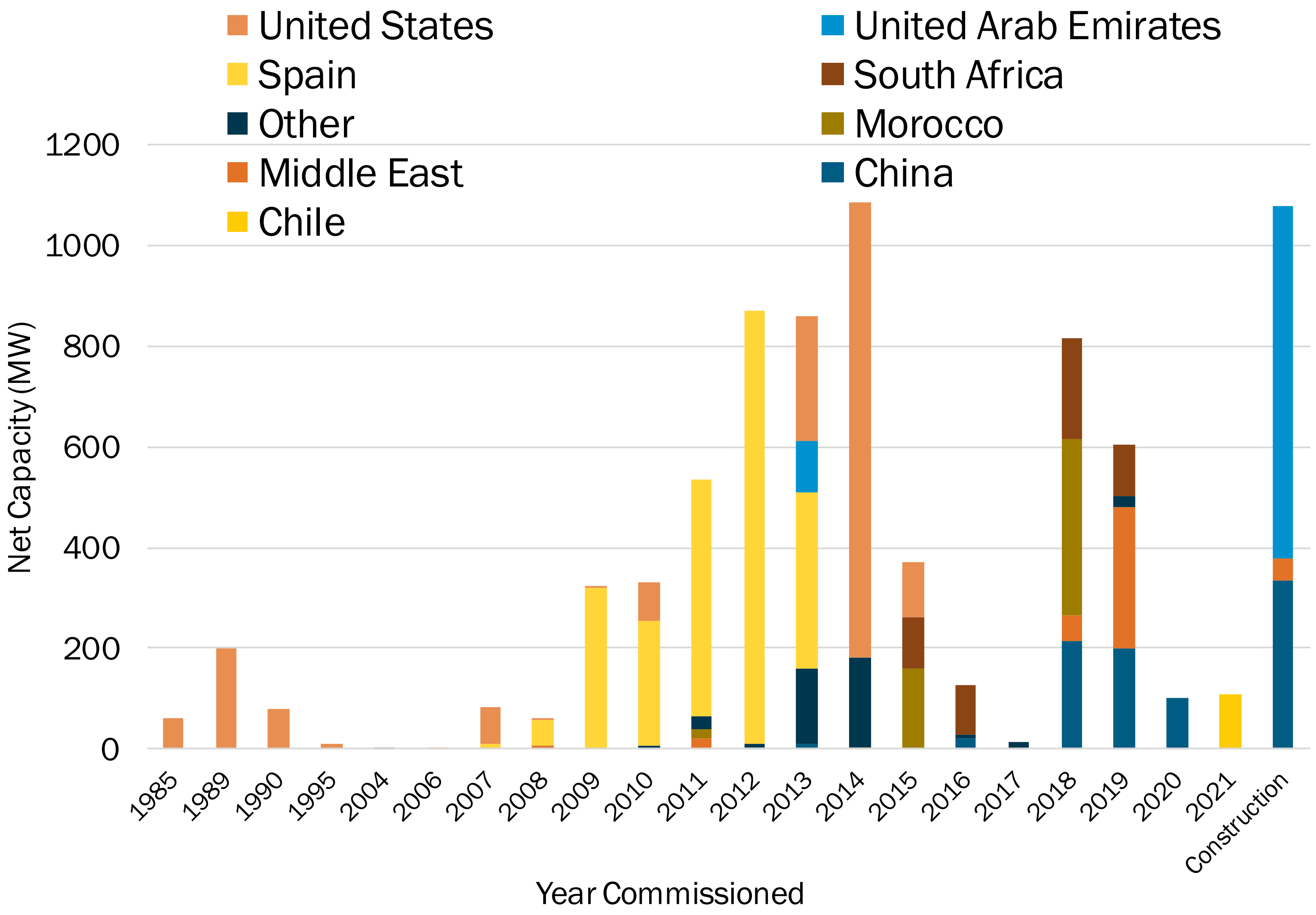
↓

'Gen 3 CSP': Novel Heat Transfer Media with advanced power cycle (>700 °C)



Documenting CSP Best Practices





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

Congratulations to the SETO FY2022 CSP FOA Awardees!

Research in Equipment For Optimized and Reliable Machinery (CSP REFORM)

Performance Optimization of Sold Particle TES Heat Exchanger by Combining Benefit of Extended Surfaces and Particle Fluidization

Brayton Energy | $1.9 million

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

Improved O&M Reliability for CSP Plants through Application of Steam Generator Damage Mechanisms Theory & Practice

Electric Power Research Institute | $1.9 million

Improved Design Standard for High Temperature Molten Nitrate Salt Tank Design

IDOM | $2 million

CSP Plant Optimization Study for the California Power Market

Solar Dynamics | $1 million

Design Basis Document/Owners Technical Specification for Nitrate Salt Systems in CSP Projects

Solar Dynamics | $450,000

Evaluation of High-Temperature Sensors for Molten Solar Salt Applications

Sporian Microsystems | $1 million

Performance Improvement in CSP Plant Operations

University of Wisconsin – Madison | $1.6 million

Scalable Outputs for Leveraging Advanced Research on Receivers & Reactors (SOLAR R&R)

Silicon-Carbide Receiver/Reactor by Additive Manufacturing for Concentrated Solar Thermocatalysis with Thermal Energy Storage

Dimensional Energy | $2.7 million

Ultra-High Operating Temperature Silicon-Carbide-Matrix Solar Thermal Air Receivers Enabled by Additive Manufacturing (Ultra-HOTSSTAR)

General Electric Company, GE Research | $2.6 million

Light Trapping, Enclosed Planar-Cavity Receiver for Heating Particles to Enable Low-Cost Energy Storage and Chemical Processes

National Renewable Energy Laboratory | $3 million

Scalable, Infiltration-Free Ceramic Matrix Composite (CMC) Manufacturing for Molten Salt Receiver

Palo Alto Research Center | $2.5 million

Intensified Solar Reactor for Green Ammonia Manufacture and Gen3 Thermochemical Energy Storage

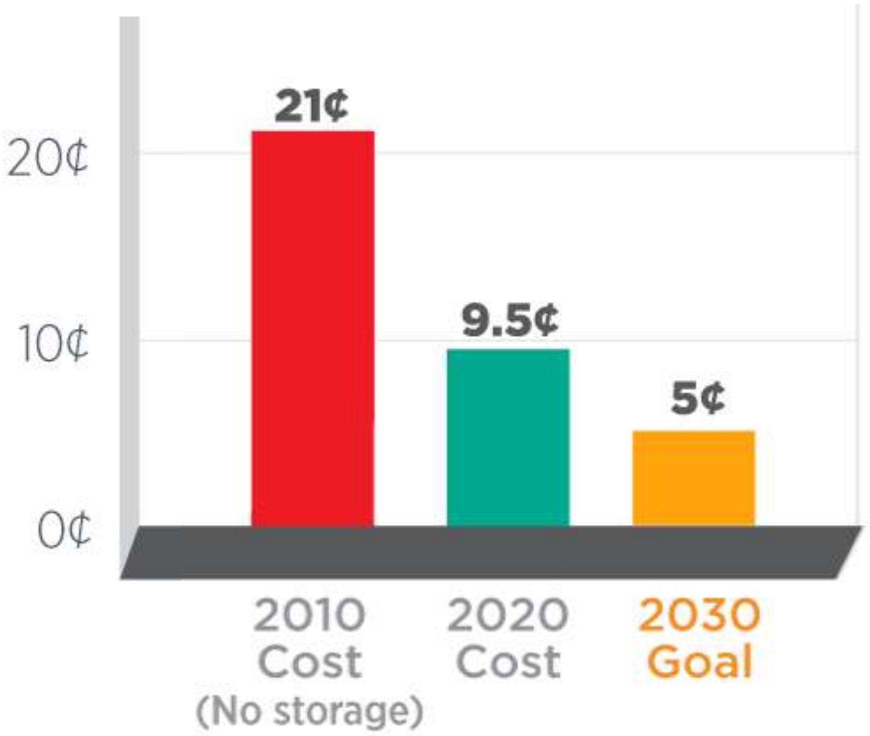
Texas Tech University | $2 million

Design and Manufacturing of Transparent Refractory Insulation for Next-Generation Receivers

University of Michigan | $2.5 million

Progress and Goals: 2030 CSP Goal

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



*Assumes a gross to net conversion factor of 0.9

Heliostat Consortium

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

NREL Transforming ENERGY

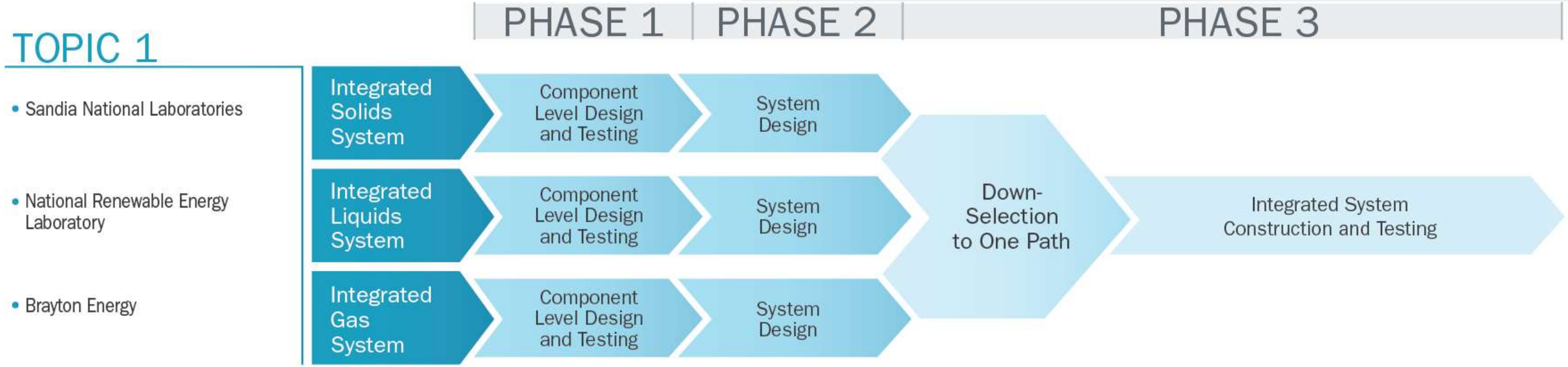
Sandia National Laboratories

ASTRI Australian Solar Thermal Research Institute

Objectives of the $25 million consortium:

- Develop strategic roadmaps for improving the cost and performance of commercial heliostats, to substantially reduce the cost of capturing solar-thermal energy
- Develop key testing capabilities to validate and optimize industrial heliostat technologies
- Fund collaborative research on heliostat innovation
- Form U.S. centers of excellence focused on heliostat technology
- Promote workforce development of the next generation of CSP researchers and industry

Gen3 CSP: Pathway Selection



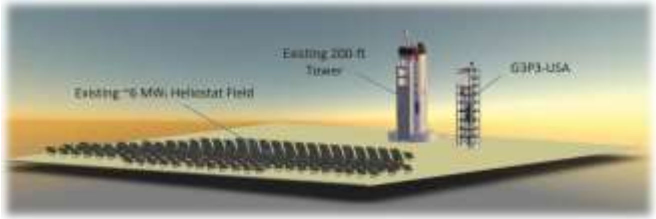
In March 2021, SETO announced that Sandia would receive $25 million to construct a MW-scale test facility at the National Solar Thermal Test Facility in Albuquerque, NM

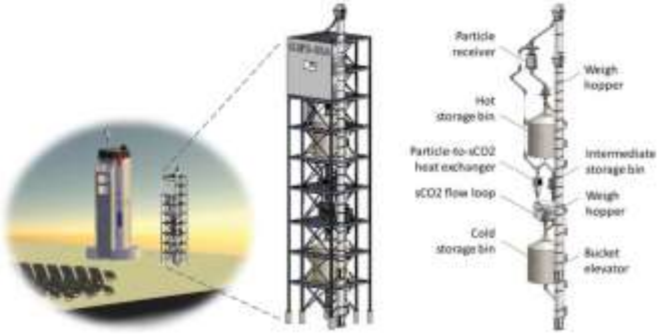
Gen3 CSP: Pathway Selection

TOPIC 1

- Sandia National Laboratories

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		





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

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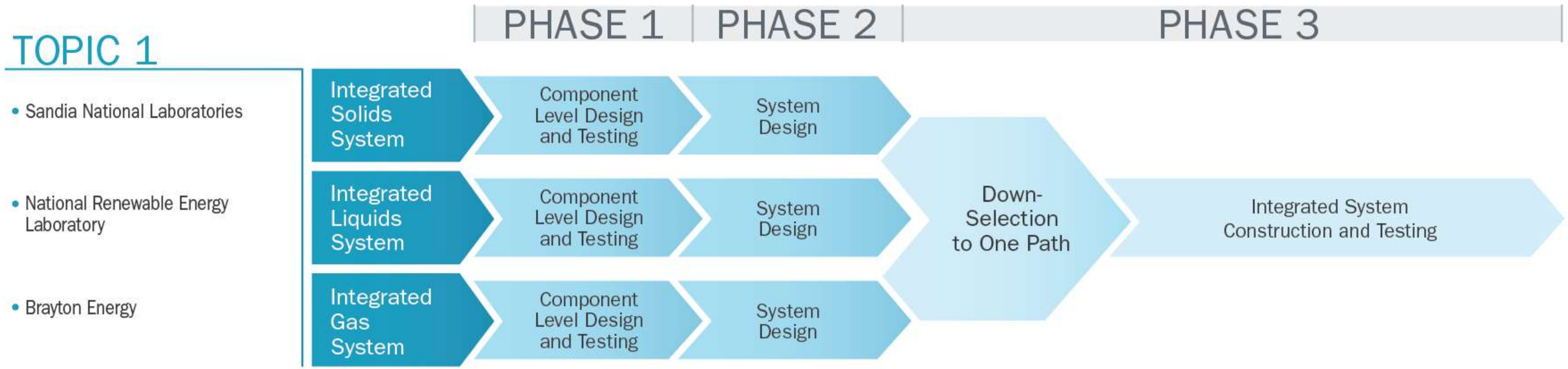
Gen3 CSP: Future Needs for Liquid and Gas Pathways



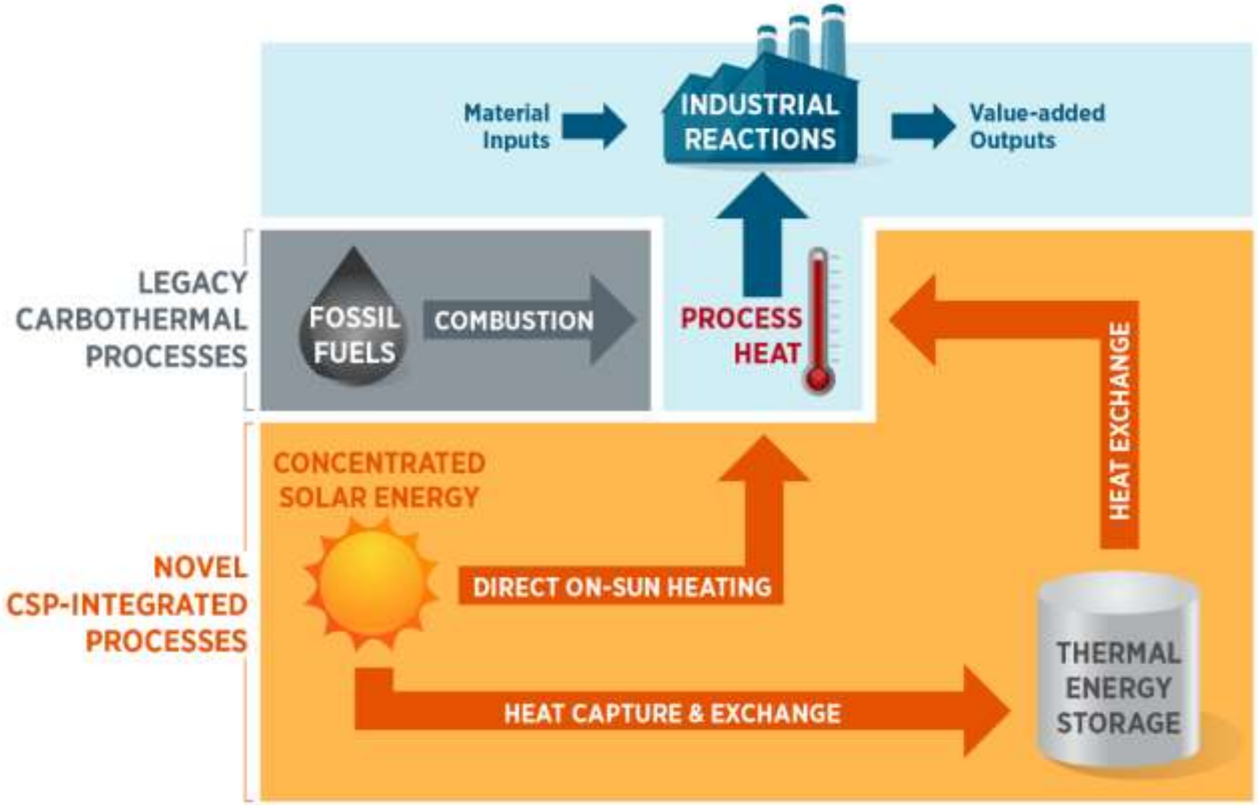
Liquid Pathway

- 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

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)

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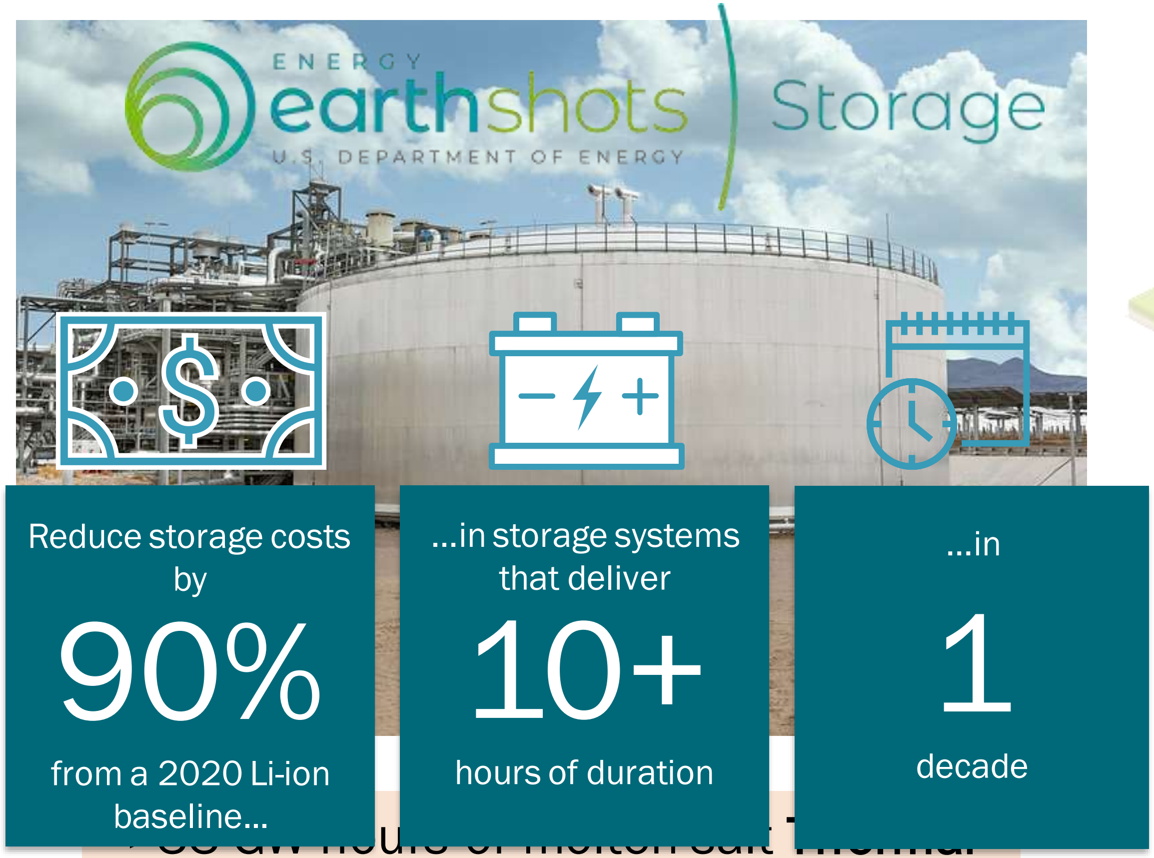
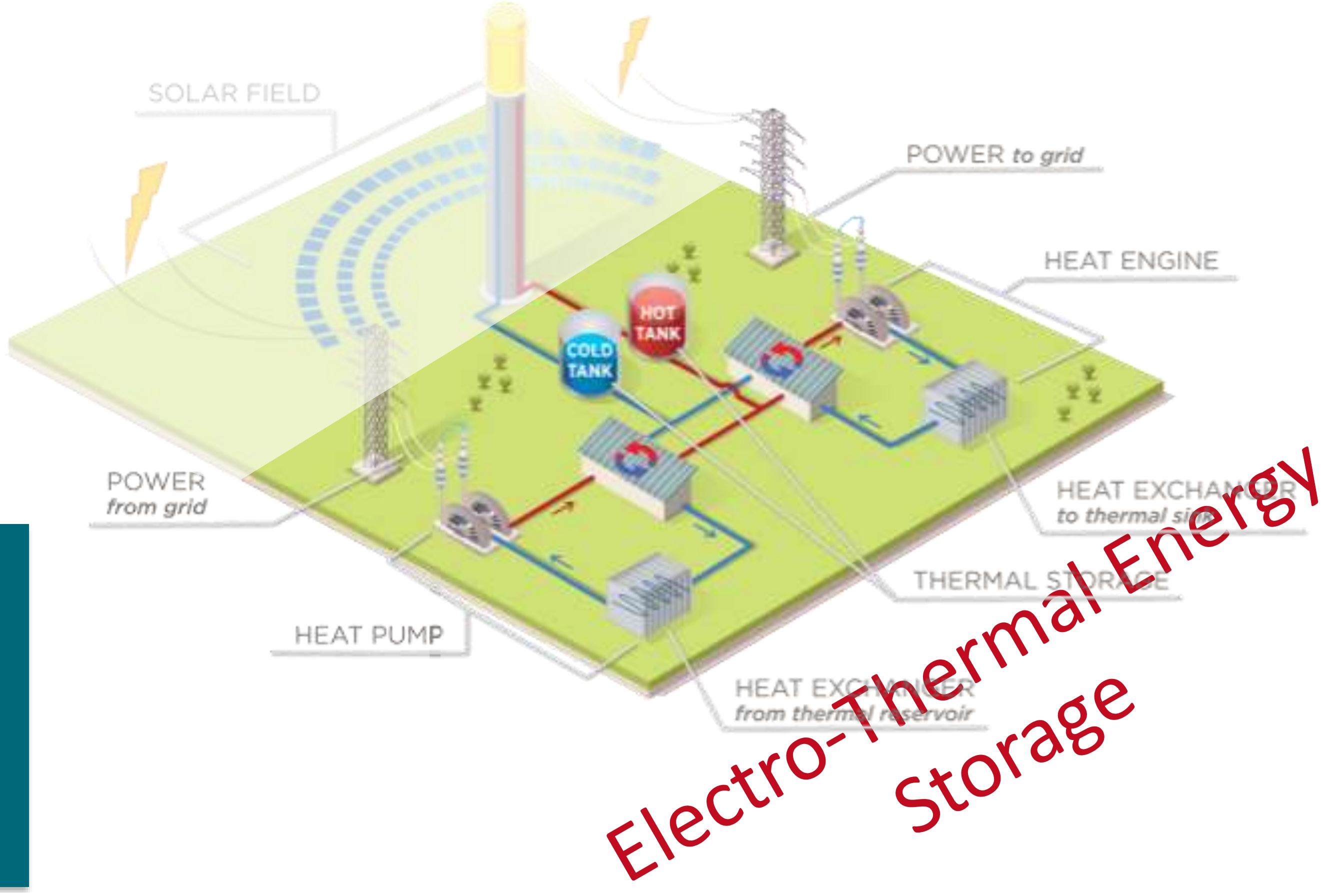
CSP and Long-Duration Energy Storage



Energy Storage operating globally



TES has a low marginal cost of additional energy capacity/duration

Congratulations to the SETO FY2022 CSP FOA Awardees!

Small Innovative Projects in Solar (SIPS) – CSP

Concentrated Solar Thermal Fuels Production by Electric Field Enhanced Two-Step Gas Splitting

Arizona State University | $310,000

Technology for Electrically Enhanced Thermochemical Hydrogen

Arizona State University | $400,000

In-Operando Thermal Transport Characterization of Moving Particle Bed Heat Exchanger

University of California, San Diego | $400,000

High-Temperature Permanent Magnet-Biased Active Magnetic Bearing Development for Supercritical Carbon Dioxide Machinery Applications

Southwest Research Institute | $400,000

Development and Experimental Optimization of High-Temperature Modeling Tools and Methods for Concentrated Solar Power Particle Systems

University of Dayton | $400,000

Spectral and Temperature-Dependent Optical Metrology: Towards More Robust, Effective and Durable Materials for Concentrated Solar Power

University of Michigan | $240,000

Development of Gas Bearings for Supercritical Carbon Dioxide Recompression Brayton Cycle

University of Nevada – Las Vegas | $250,000

Innovative Technology for Continuous, Online (In Situ) Monitoring of Corrosivity of Molten Salts to Prevent Catastrophic Failure of Solar Thermal Plants

University of Nevada – Reno | $400,000

Low-Cost Heliostat for High-Flux Small-Area Receivers

University of Wisconsin – Madison | $330,000

Pumped Thermal Energy Storage (PTES)

Advanced Ice Slurry Generation System for a Carbon Dioxide–Based Pumped Thermal Energy Storage System

Echogen Power Systems | *$1.2 million*

Characterization of Inlet Guide Vane Performance for Discharge Compressor Operation near the Dome of an sCO_2 Pumped Heat Electricity Storage

Southwest Research Institute | *$500,000*

Development of a Multiphase-Tolerant Turbine for Pumped Thermal Energy Storage

Southwest Research Institute | *$2.4 million*

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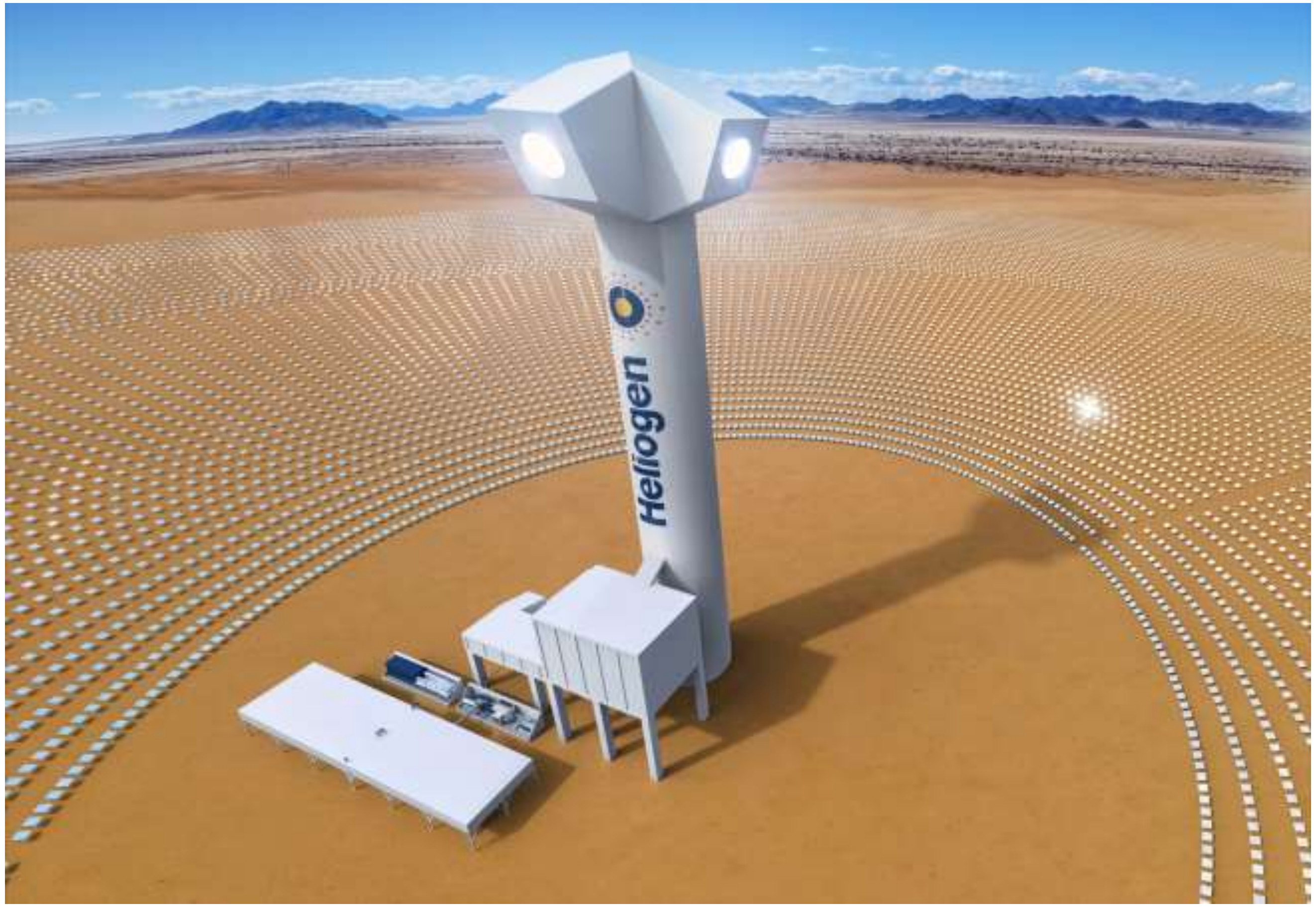
Advanced Power Cycles

*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

Integrated TESTBED (*T*hermal *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

CJ Kalra

Vice President
Power Generation Engineering
Heliogen, Inc.

Control Number: 2243-3521

Funding Opportunity Announcement DE-FOA-0002243
Topic Area 2: Integrated Thermal Energy STorage and Brayton cycle Equipment Demonstration (Integrated TESTBED)

Development, Build and Operation of a Full-Scale, Nominally 5MWe, Supercritical CO_2 Power Cycle Coupled with Solid Media Energy Storage

Submitted by
Heliogen Inc.
Pasadena, CA 91103

Technical Point of Contact
Dr. Chiranjeev Kalra (Principal Investigator)

Business Point of Contact
Mr. Vikas Tuteja

OBJECTIVE

Development, Build and Operation of a Full-Scale, Nominally 5MWe, Supercritical CO_2 Power Cycle Coupled with Solid Media Energy Storage

- Thermal energy storage using sensible energy storage in solid media
- sCO_2 RCBC heat engine with air cooling
- Demonstrate the integrated performance of all the heat exchangers in an indirectly heated sCO_2 cycle
- Perform a testing campaign and data validation necessary to generate commercial confidence in operational standards for sCO_2 power blocks

Power Block Efficiency Roadmap >39%

TIT < 630°C

CAPEX Roadmap <$900/kWe

Air-cooled

>1,000 hours of testing

Demonstrate fast-transients and load following capability

>5% load ramp per minute from cold start

Concentrated Solar Power – Modular, Long Duration Storage

- Build on state-of-the art sCO_2 power cycle developments: SunShot, Apollo, STEP
- Leverage solid media based thermal storage solutions
- Integrated system development and risk retirement testing followed by commercial operation
- Overall approach guided by Voice of Customer

Confidential – Do Not Distribute

Towards SETO CSP Target
Product Development and Commercialization Plan

- Thermal energy storage coupled with CSP already competitive w/ natural gas for thermal applications

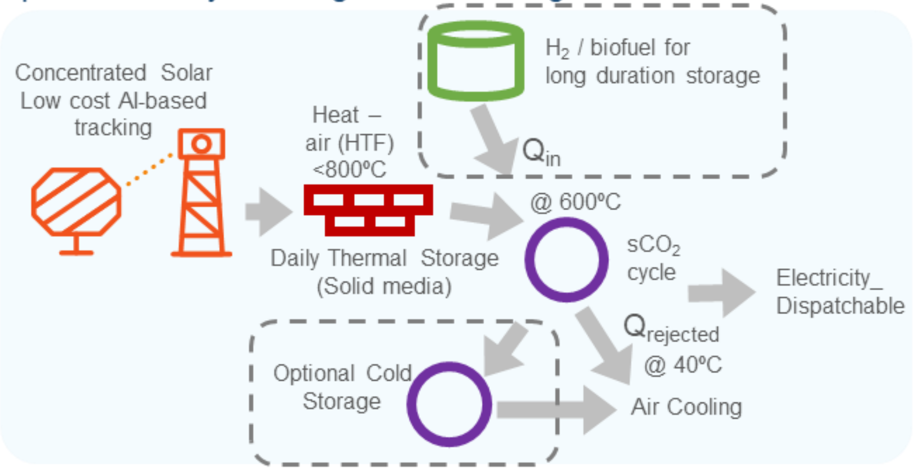
- CSP electricity production enables long duration energy storage in thermal storage systems and seasonal storage in chemical fuels like Hydrogen

STAGE 1
DOE SETO 2020 Proposal
42-month performance period to build and operate the 1st power plant

STAGE 2
Autonomous manufacturing and scale-up of production

STAGE 3
Incremental technology and cost improvements

Product block diagram: Integrated, hybrid, modular solar power plant with daily and long duration storage



Confidential – Do Not Distribute
REPLACING FUELS WITH SUNLIGHT
Heliogen

Demonstration Plant:
Small Modular Power Block Size

Examples:

Simple cycle gas turbines don’t necessarily need larger scales to provide optimal product configurations

- LM2500 and LM6000 aero-derivatives used in power generation haven’t scaled-up while the original aviation engines have evolved into GE90 (90MWe), GE9X (110MWe), etc.

Combined Cycle power plants have scaled to larger sizes due to limitations of Steam cycles

- Steam power plants don’t scale down well (locative engines with few 100-kW power are a good example
- Combined cycle power plants are designed for optimal performance of both steam and Brayton cycles at the same size – easy to achieve at larger scales, single steam cycles are often coupled with multiple GT’s

References:
23. Battisti, Erica, et al. "Economical considerations about combined cycle power plant control in deregulated markets." International Journal of Electrical Power & Energy Systems 28.4 (2006): 284-292.
24. Owens, Brandon. "The rise of distributed power." General Electric 47 (2014).

Small Modular Power Block Size: TOP 3 Benefits

In addition to providing 24-7 power for industrial customers, modular power block enables:

- Ease of project financing and rapid installation: frequent design iteration capability
- Project size: small modular: most developers can participate
- Ease of permitting with lower environmental risk: higher efficiency fields, smaller & flexible land requirements

System Design and Development:

Heliogen to lead systems design

- Close collaboration with sub-system OEMs
- Optimization for net product value (cost versus performance) with emphasis on roadmap

Transient systems design

- The team will develop design point and off-design performance maps to deliver optimal product configuration metrics and requirements

Requirements Management

- With traceability, risk assessment, mitigation planning, change management, and frequent communication due to integral (system) nature of the product

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TIT < 630^{o}C

CAPEX Roadmap <$900/kWe

Air-cooled

>1,000 hours of testing

Demonstrate fast-transients and load following capability

>5% load ramp per minute from cold start

Technology Description:
sCO_2 Power Block

Broad design range

- 4-10 MWe modular, to 100+Mwe

High efficiency

- 39%+ possible with mostly SS construction

Low operating cost

- Potential for low utility design: no oil changes, remote operation, etc.

Low specific cost

- <$900/kWe possible with volume production

Technology development risk

- New technology in the market

Raw material cost management

- High pressure sCO_2 operation more likely to require high-cost alloys

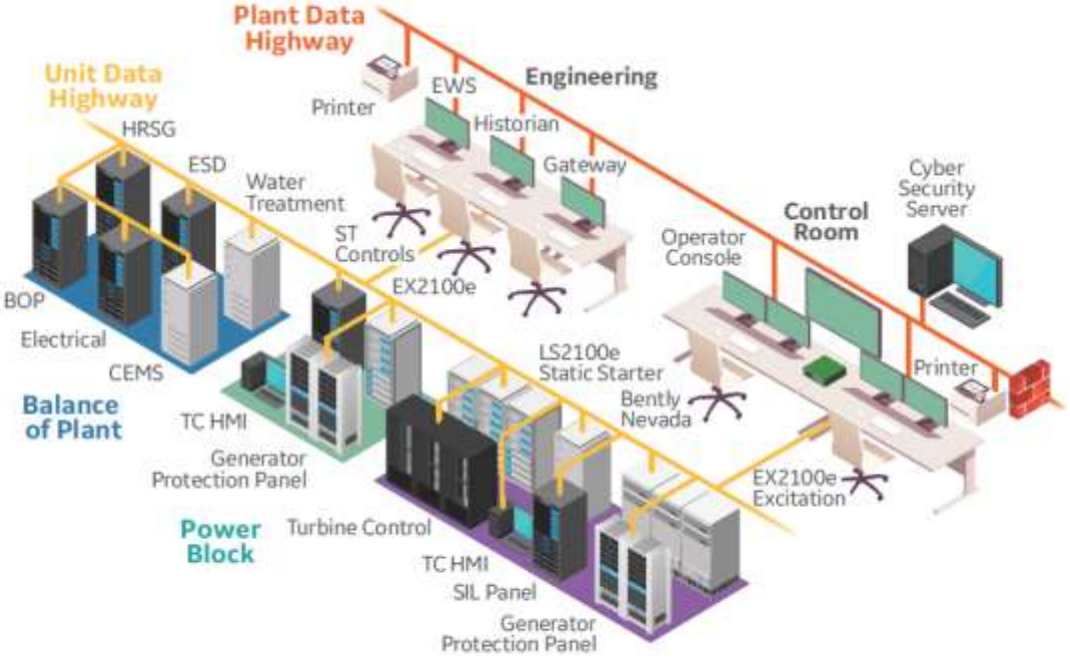
Operational risks

- With machine reliability and integration with overall power plant

Power Block – TES Integration

Integrated Control Architecture

- TES systems by definition have high thermal inertia.
- Conversely, sCO_2 power blocks, with their superior power density, have a very low mechanical (rotating) and thermal inertia to transients and can respond very fast.
- These systems need to be integrated into highly variable source and sinks.
- The proposed controls architecture will leverage an industrial Mark VIe controller from GE for integrated power block – TES control to meet the described unique requirements.



TESTBED Heat Source: Heliogen CSP System

- Cost competitive with natural gas heat source
- Commercially demonstrated technology

TESTBED CSP Plan:

- Up to 48 MW_{th}
- 50,300 small heliostats
- ~220-foot tower

Project Management Plan

Phase 1
Detailed Design
12 Months

- Integrated system optimization
- Detailed Design

Phase 2
Fabrication, Manufacturing, & Construction
15 Months

- Manufacturing
- Heat Source Installation
- Construction

Phase 3
Commissioning, Operations, & Testing
15 Months

- Commissioning
- Integrated system tests

Power Plant Product & Test-Site Design, Optimization, and Construction (Sandia National Laboratories, Heliogen)

Conceptual Design > Detailed Design > Fabrication > Test Data Analysis

Power Block and Turbomachinery Development (Barber Nichols, SwRI)

Conceptual Design > Detailed Design & Drawings > Fabrication > Test & commission

Thermal Energy Storage Design, Optimization and Construction (Sandia National Laboratories)

Conceptual Design > Detailed Design & Drawings > Fabrication > Test & commission

Testing and Site Operations (Heliogen)

Plant Construction > Mechanical Acceptance Testing > Test Execution

Objective: Near 24-7 Renewable Power Generation for Industrial and other customers

Thank You

QUESTIONS

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