U.S. DEPARTMENT OF ENERGY

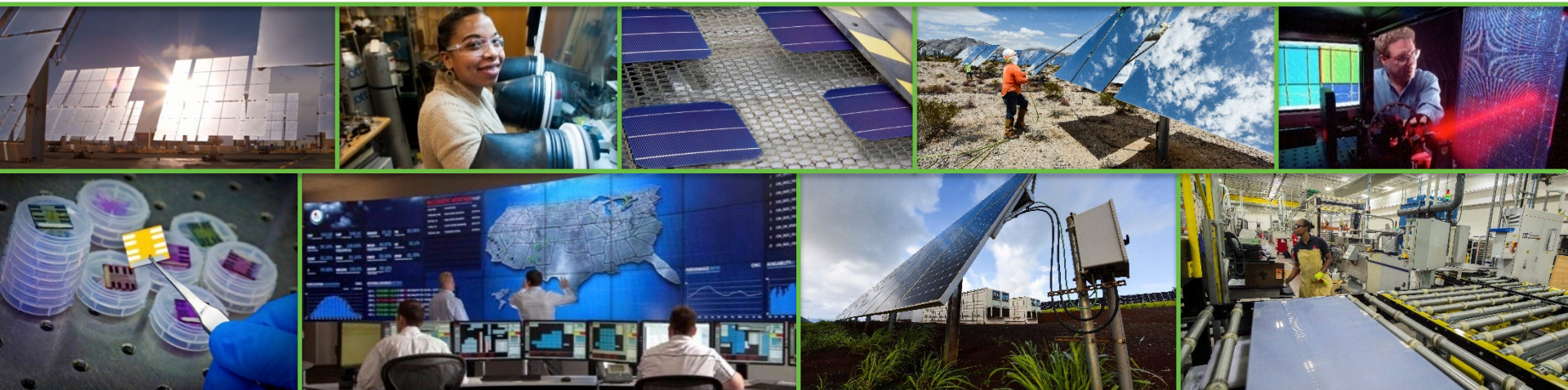
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

8th International sCO_2 Power Cycles Symposium
February 27th, 2024
San Antonio, Texas

The Development of the sCO_2 Power Cycle for Concentrating Solar Power

Matthew Bauer, DOE Program Manager

Solar Energy Technologies Office



SETO 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.

DOE Concentrating Solar-Thermal Power Team

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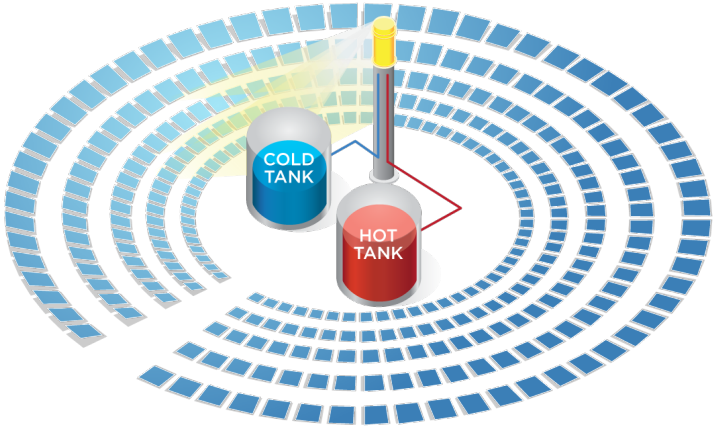
CSP affects communities.

The **Justice40 initiative** states that "40 percent of the overall benefits" of certain federal investments flow to disadvantaged communities. These investments include those for clean energy and energy efficiency that are allocated by SETO.

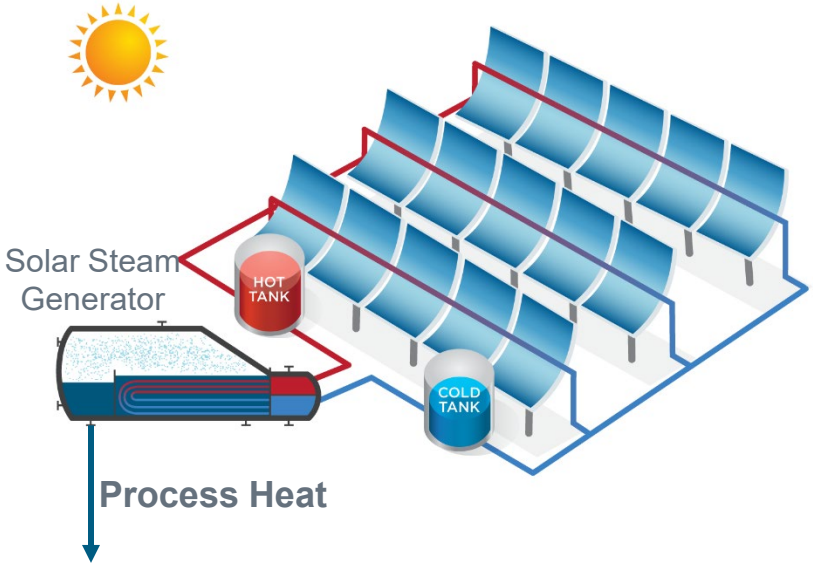
Links: Overview of Justice40 initiative; Executive Order 14008

Concentrating Solar-Thermal Technology for Power and Heat-Based Applications

BASELOAD POWER
(≥12 hours of storage)



SOLAR PROCESS HEAT

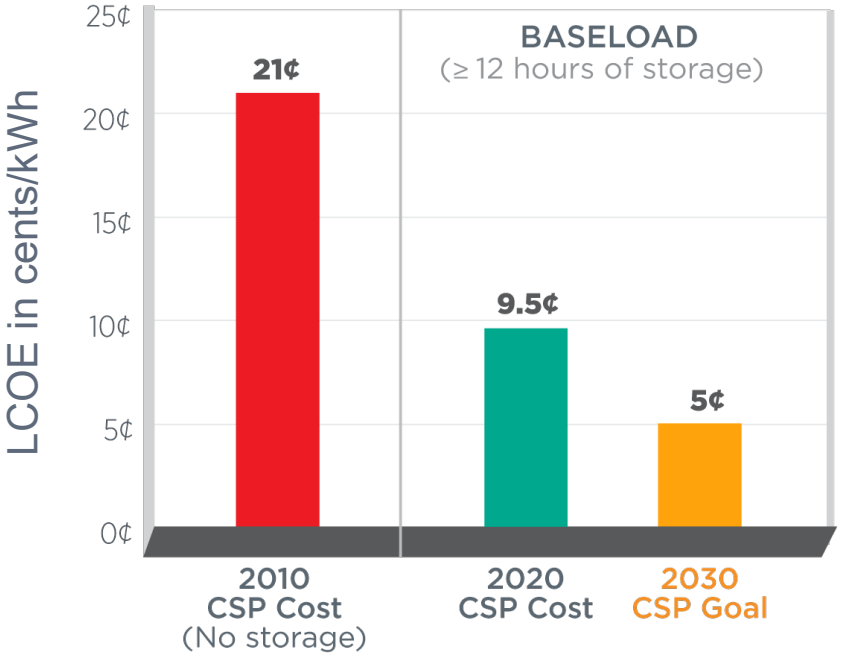


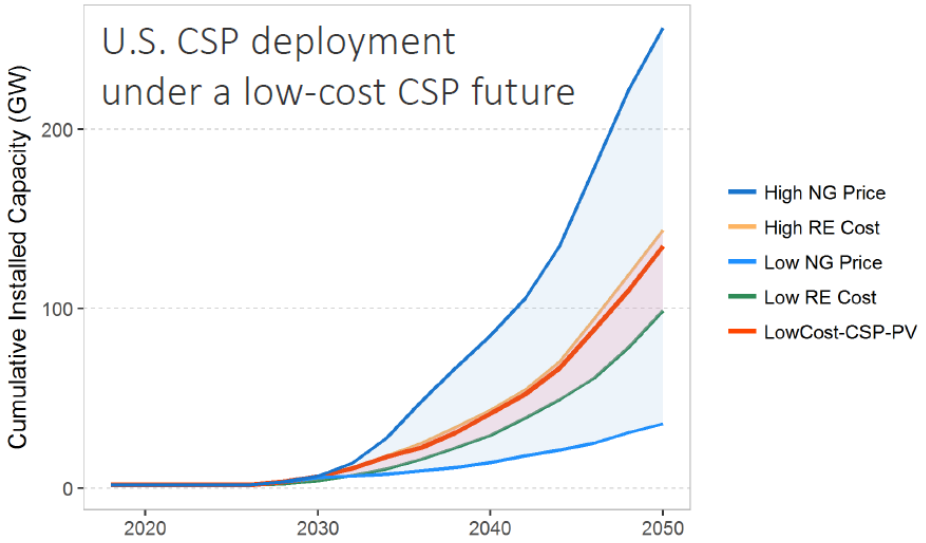
Thermally-Driven Industrial Processes:

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

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.



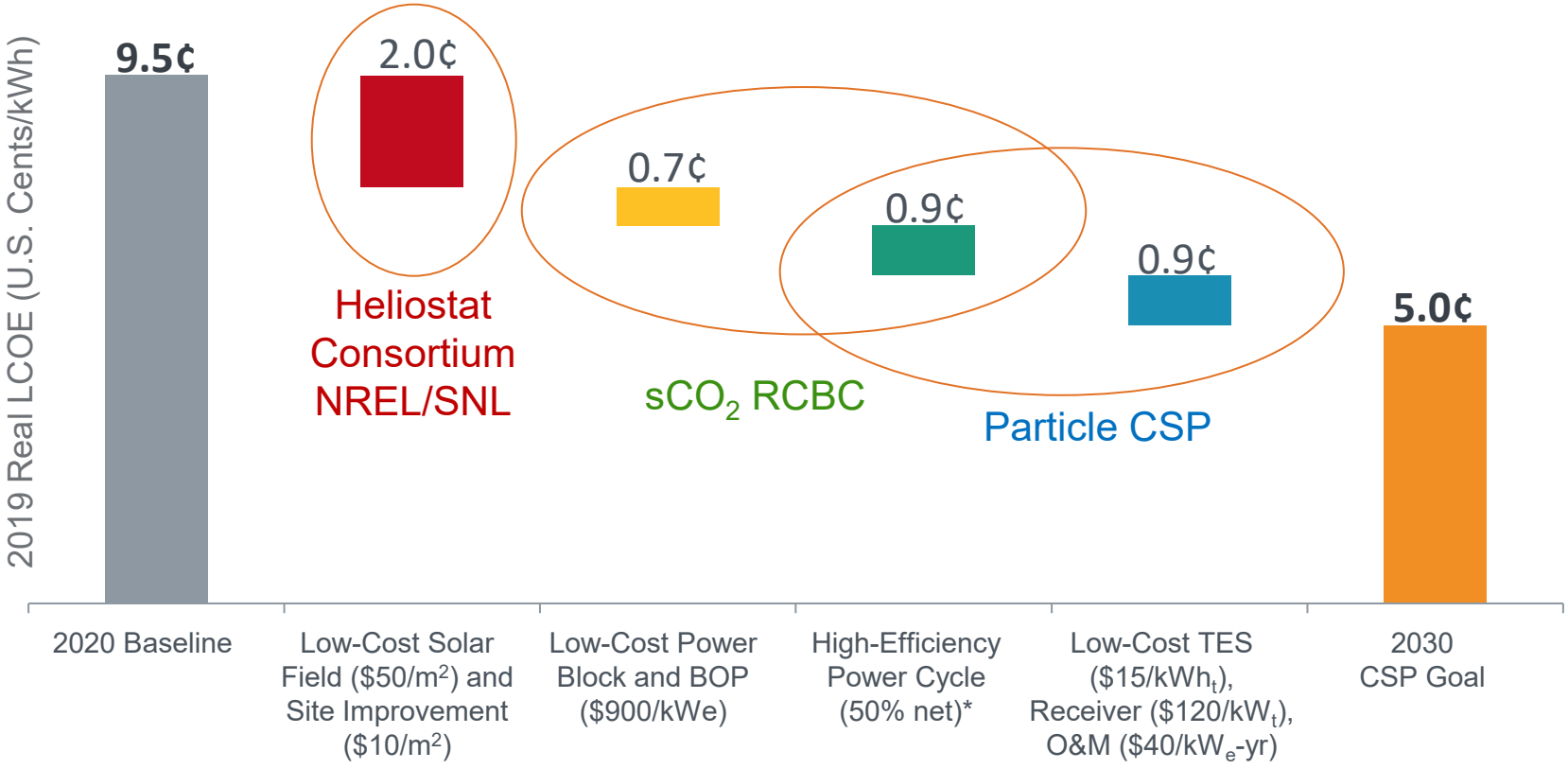


Murphy, et al. **2019**, NREL/TP-6A20-71912

*Levelized cost of energy (LCOE) progress and targets are calculated based on scenarios without federal tax credit or state/local incentives.

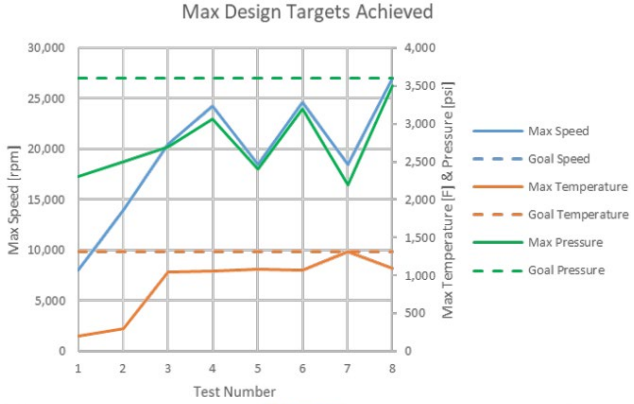
Study prior to passage of the Inflation Reduction Act

A Pathway To 5¢ per kWh for CSP



SwRI/GE's SunShot Turbine

Moore, Jeff. Development of a High-Efficiency Hot Gas Turbo-expander and Low-Cost Heat Exchangers for Optimized CSP Supercritical CO2 Operation. United States: N. p., 2019. Web. doi:10.2172/1560368.



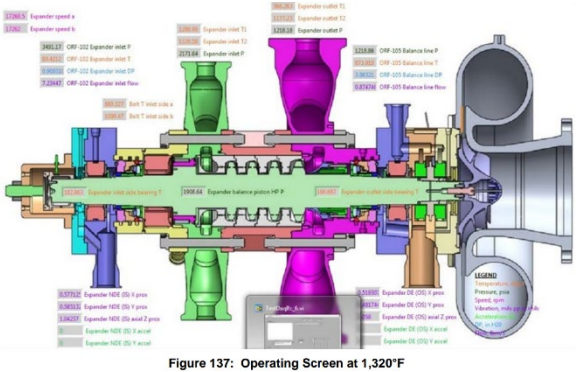
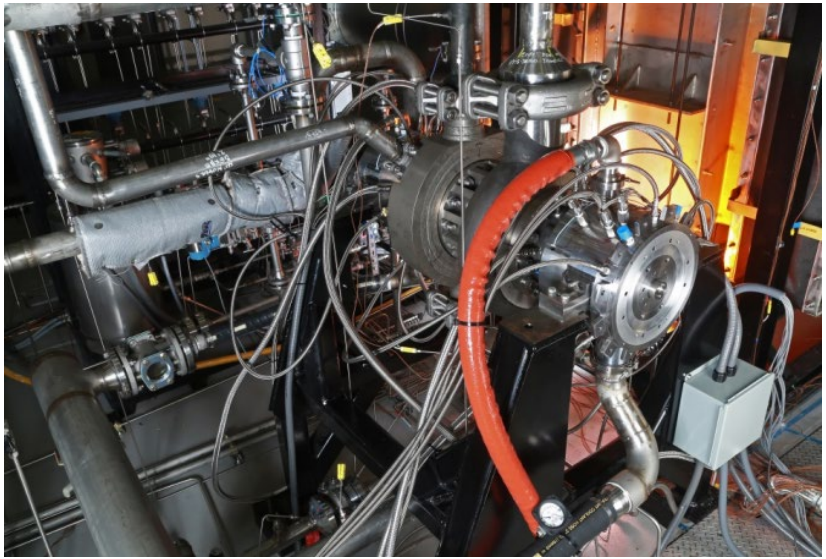
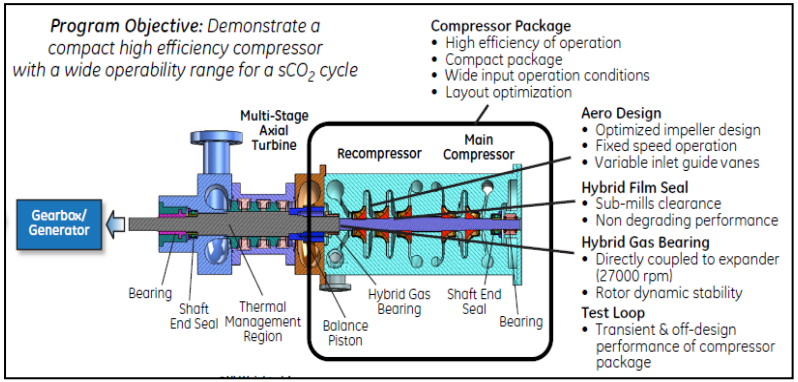


Figure 137: Operating Screen at 1,320°F

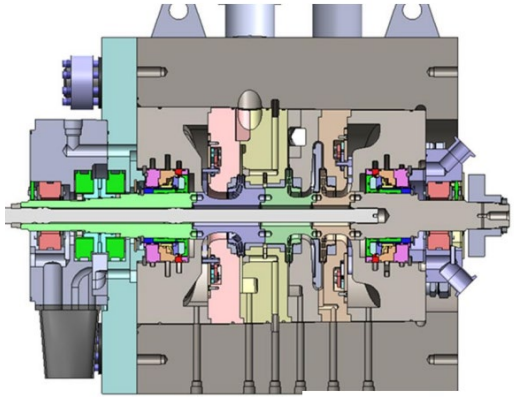


- MW scale sCO_2 loop
- Achieved targets of 1,320°F, 27,000 rpm, and 3,500 psi in separate tests
- 37.5 hours of turbine operation
- sCO_2 turbo-expander and heat exchangers successfully fabricated
- Replicated transient conditions consistent with CSP use

GE & SwRI's Apollo sCO_2 Centrifugal Compressor

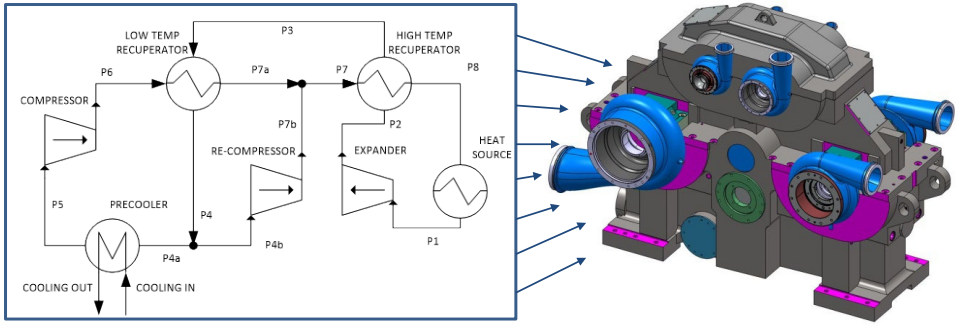


- MW scale compressor design and test
- 720 kg/m^3, a world record for compressor density
- Design and fabrication of 80% design point efficiency compressor
- Nearly all components behaved well mechanically demonstrating high pressure/density compression is viable beyond traditional rotor dynamics limits
- Identified major R&D priorities including:
  - Dry Gas Seals materials development
  - CO_2 property and measurement understanding near the liquid-vapor dome
  - Impact of deflections within internal hardware



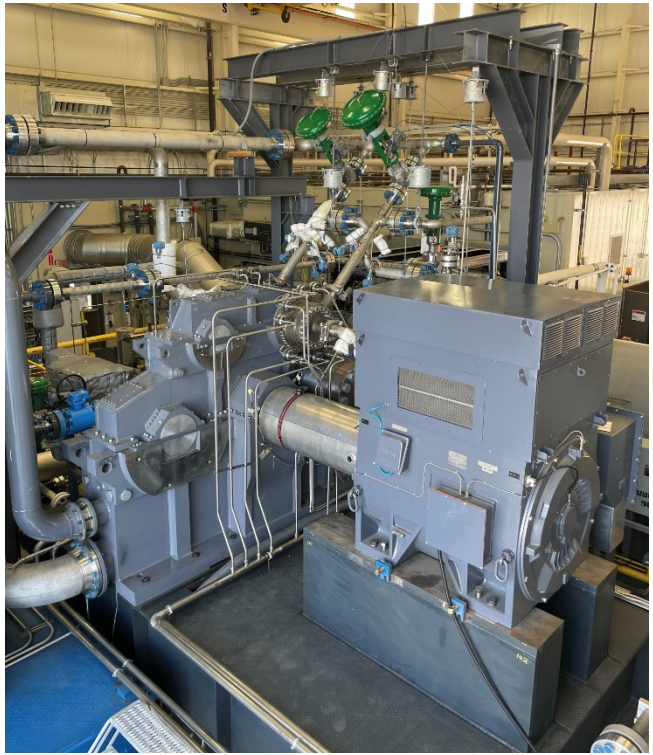
1) Neveu, Joshua D., et al. "Operation and Control of a Supercritical CO2 Compressor." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 85048. American Society of Mechanical Engineers, 2021.
2) Cich, Stefan D., et al. "Mechanical Design and Testing of a 2.5 MW SCO2 Compressor Loop." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 85048. American Society of Mechanical Engineers, 2021.
3) Mortzheim, Jason, et al. "Challenges with measuring supercritical CO2 compressor performance when approaching the liquid-vapor dome." *Turbo Expo: Power for Land, Sea, and Air*. Vol. 85048. ASME, 2021.

Development of an Ultra-High Efficiency Integrally-Geared Supercritical CO_2 Compander



Hanwha Techwin

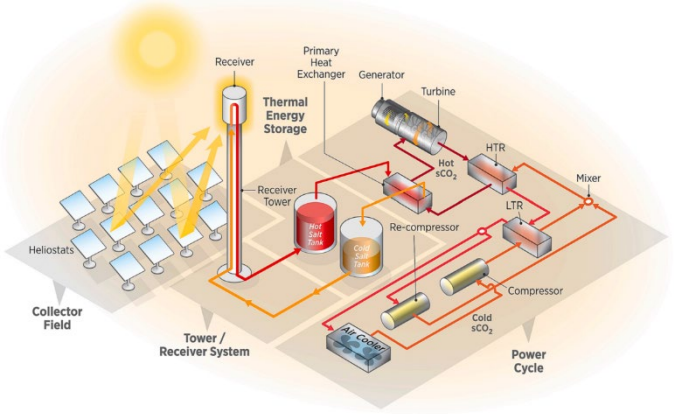
SwRI



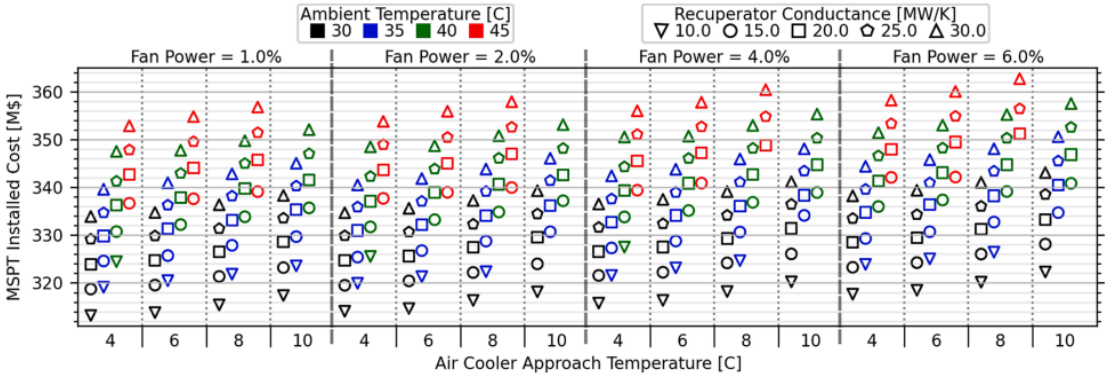
- Highest pressure sCO_2 DGS in the world
- Highest pressure integrally geared expander
- Highest density integrally geared expander
- Highest density radial expander
- Highest temperature radial expander at pressure > 100 bar
- Highest pressure integrally geared compressor
- Highest density integrally geared compressor
- First functional sCO2 compressor driven turbine power cycle loop > 1MW

Detailed Cycle and Plant Modeling for CSP cases

NREL's System Advisor Model



Optimization accounting for off design performance



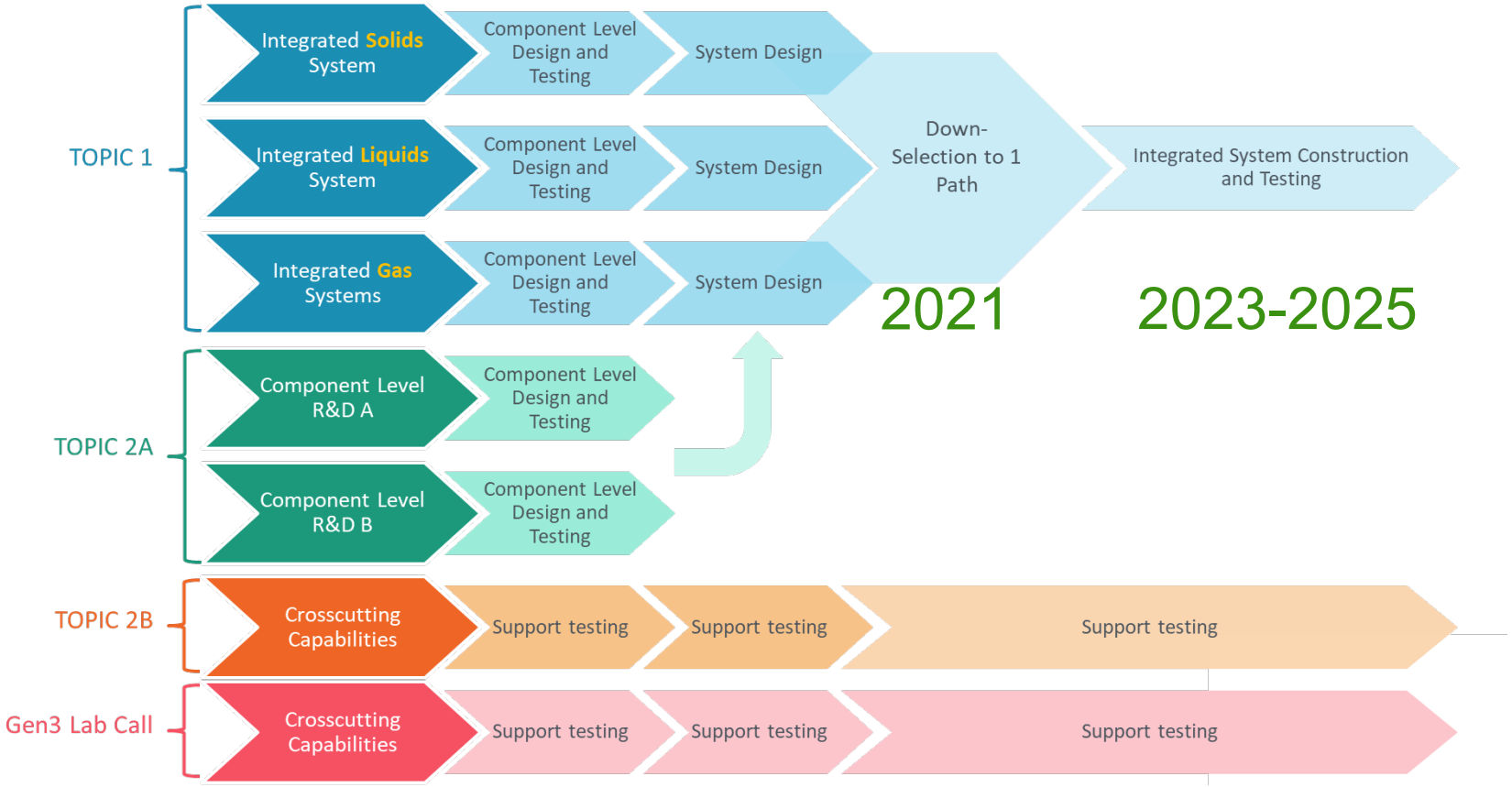
Neises, Ty. "Steady-state off-design modeling of the supercritical carbon dioxide recompression cycle for concentrating solar power applications with two-tank sensible-heat storage." *Solar Energy* 212 (2020): 19-33.

Augustine, Chad, Kurup, Parthiv, Mehos, Mark, and Neises, Ty. FY19-FY21 Concentrating Solar Power Systems Analysis Final Report. United States: N. p., 2023. Web. doi:10.2172/1923360.

https://github.com/NREL/SAM/blob/develop/samples/CSP/sco2_analysis_python_V2/example/User_Guide.pdf


Gen3CSP
Bringing together the people and the pieces for an INTEGRATED CSP SYSTEM
SunShot
U.S. Department of Energy

SETO's Gen3 CSP Program Structure (2017)

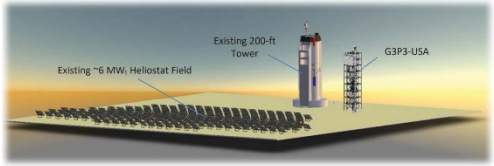


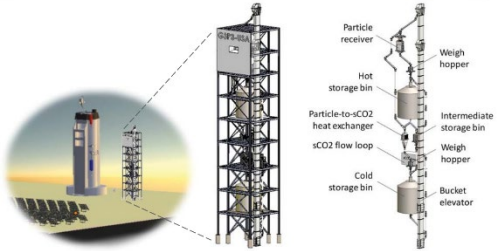
Gen3 CSP Pathway Selection: Particles

TOPIC 1

- Sandia National Laboratories

	PHASE 1	PHASE 2	PHASE 3
		2021	2023-2025
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 temperature operating range and relevant to other thermal applications
- Less expensive TES and less reliance on expensive alloys

Remaining Gaps:

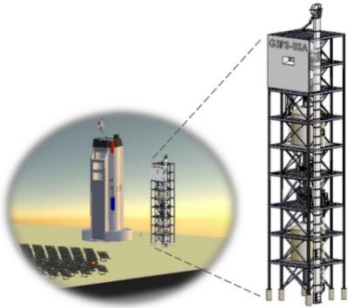
- Receiver optimization
- Particle cost
- Demonstrations of flow control and particle handling at scale
- Increasing system ΔT
- Particle Erosion & Abrasion
- Particle / sCO_2 Heat Exchanger

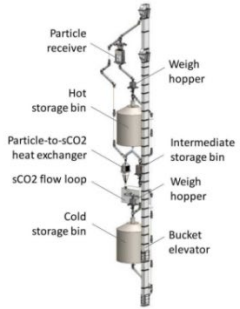
Gen3 Particle Pilot Plant (G3P3 Construction) 2023-2024

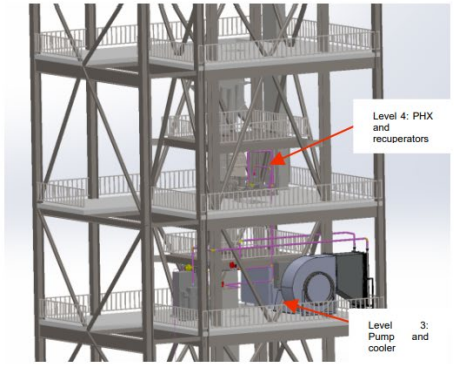
- Existing NSTTF Heliostat Field
- Direct Falling Particle Receiver 1-2 MW_{th}; 775°C
- 6 MWh Thermal Energy Storage (Gravity Fed)
- Diffusion Bonded Moving Packed Bed sCO_2 / Particle Heat Exchanger 550 to 720 °C
- 1 MW_{th} 700°C sCO_2
- Continuous Particle Elevator

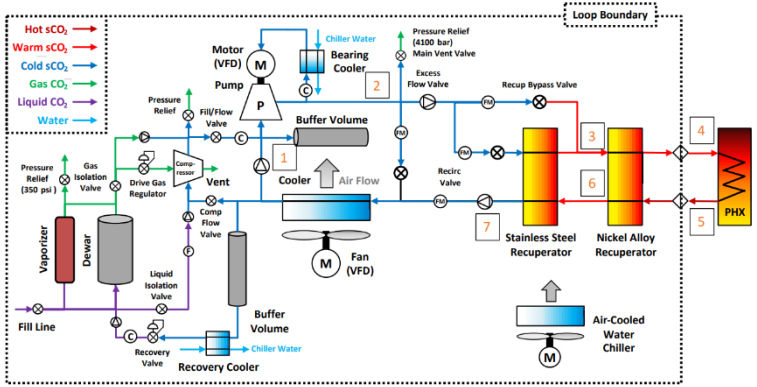
Photo Credits to Sandia National Laboratories, Jeremy Sment, Margaret Gordon, and Ken Armijo

G3P3 sCO_2 loop









Alvarez, Francisco. Integration of Supercritical Carbon Dioxide Cooling Loop for G3P3 Primary Heat Exchanger. United States: 2022.

In 2023 the DOE's Office of Clean Energy Demonstrations Selected and began negotiations with SNL to add a ~100kW turbine to the sCO_2 loop

Integrated TESTBED Thermal Energy Storage & Brayton Cycle Equipment Demonstration

2021- Heliogen's Capella Project Launches:

Particle + sCO_2 Demonstration

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 > 10,000 heliostats, > 15 MW_{th}
- At least 50 MWh_{th} Thermal Energy Storage

TESTING CAPABILITY

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

SETO sCO_2 activities and opportunities

- December-February sCO_2 Request For Information

https://eere-exchange.energy.gov/Default.aspx#FoaId69a8a2bc-43d6-4066-9165-df4595b8ccd6

(Or just search "SETO sCO2 RFI")

- Small Business Innovation Research (SBIR) Topic Area "Supercritical CO_2 Cycles"
- Open now Small Innovative Projects in Solar (SIPS) Academic FOA. (Apps due March 6th)

Apply for funding through the

SMALL INNOVATIVE PROJECTS IN SOLAR (SIPS) PROGRAM

Think outside the box. Nearly any solar energy technology idea is eligible. SIPS aims to improve:

Funding up to $400,000

Concentrating Solar-Thermal Power

- Thermal energy storage
- Solar-thermal industrial processes
- Solar-thermal fuels
- Solar collectors (e.g. heliostats)
- Turbomachinery

Funding up to $250,000

Photovoltaics

- Power conversion efficiency
- Field performance
- Service lifetime
- Manufacturability
- Reuse and recycling

Produce significant results in 12-18 months

Quickly validate novel concepts

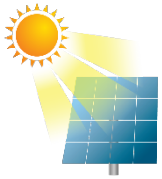
Lay the foundation for later-stage research and development

Learn more:
energy.gov/eere/solar/small-innovative-projects-solar-sips-program

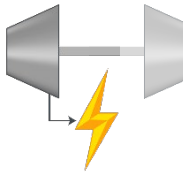
Concentrating Solar Flux to Heat and Power

Notice of Intent Published 2/26/24

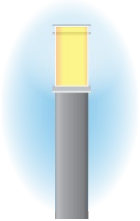
EERE plans to issue the FOA in or about March 2024 via the EERE eXCHANGE website https://eere-eXCHANGE.energy.gov/.



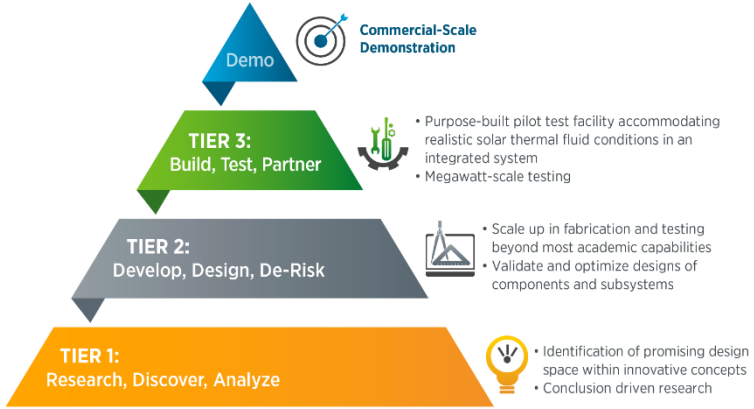
Topic Area 1: Scalable Concentrating Solar Collectors seeks advanced collector concepts that can enable a low cost and reliable integrated collector field. SETO is interested in innovations to decrease the installed costs of solar collectors to $50 per square meter with high reliability and efficiency over a 30-year lifetime. Heliostat systems, line-focusing collectors, and other novel collector forms are of interest.



Topic Area 2: Scalable Supercritical Carbon Dioxide (sCO_2) Turbomachinery seeks proposals to mature the technology readiness level (TRL) of viable turbines and compressors for the specified power cycle. SETO is interested in proposals for RD&D to enable the deployment of sCO_2 turbomachinery for advanced CSP systems. Multiple heat engine and heat pump cycles are of interest to enable cost effective CST plants coupled with thermal energy storage.

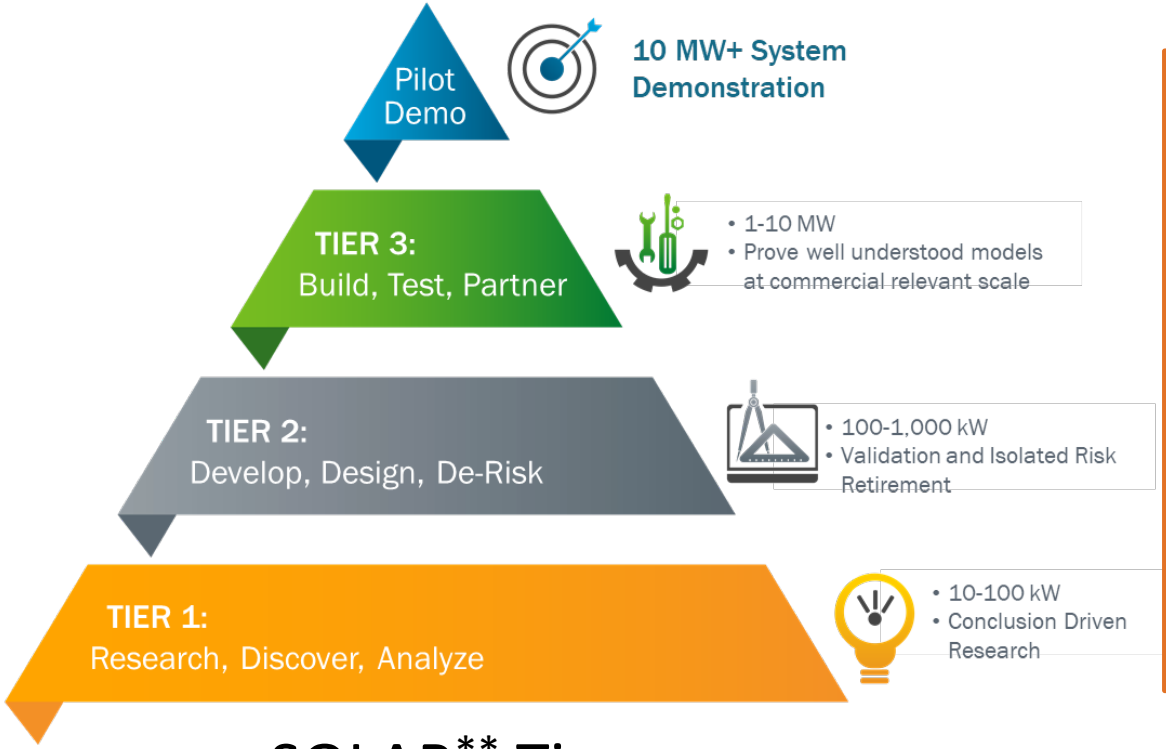


Topic Area 3: Scalable Concentrating Solar-thermal Receivers and Reactors seeks innovative receiver or reactor concepts that could enable new CST systems, as well as the development of receivers to improve existing CSP systems. SETO is interested in proposals for novel solar receivers, solar reactors, and improvements to existing solar receiver concepts. Successful receiver or reactor technologies will support the deployment of CST systems that can benefit the U.S. market.



- SOLAR Tier 1: up to $3 million federal funds
- SOLAR Tier 2: up to $5 million federal funds
- SOLAR Tier 3: up to $10 million federal funds

Learning from our Gen3 CSP Program execution



- The Gen3 CSP program succeeded in focusing the research communities, down selecting technologies, and bringing the best out of competitive R&D teams.
- But it required a very rigid top-down structure in pursuit of a singular purpose.
- SOLAR Tiers structure allows technologies to organically advance in scale.

SOLAR** Tiers

**Scalable Outputs for Leveraging Advanced Research

SETO Newsletter – Stay in Touch

- The SETO newsletter highlights the key activities, events, funding opportunities, and publications that the solar program has funded.

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SOLAR ENERGY TECHNOLOGIES OFFICE

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Solar Energy Technologies Office

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February 27, 2024

energy.gov/solar-office