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

U.S. DEPARTMENT OF ENERGY | Fossil Energy

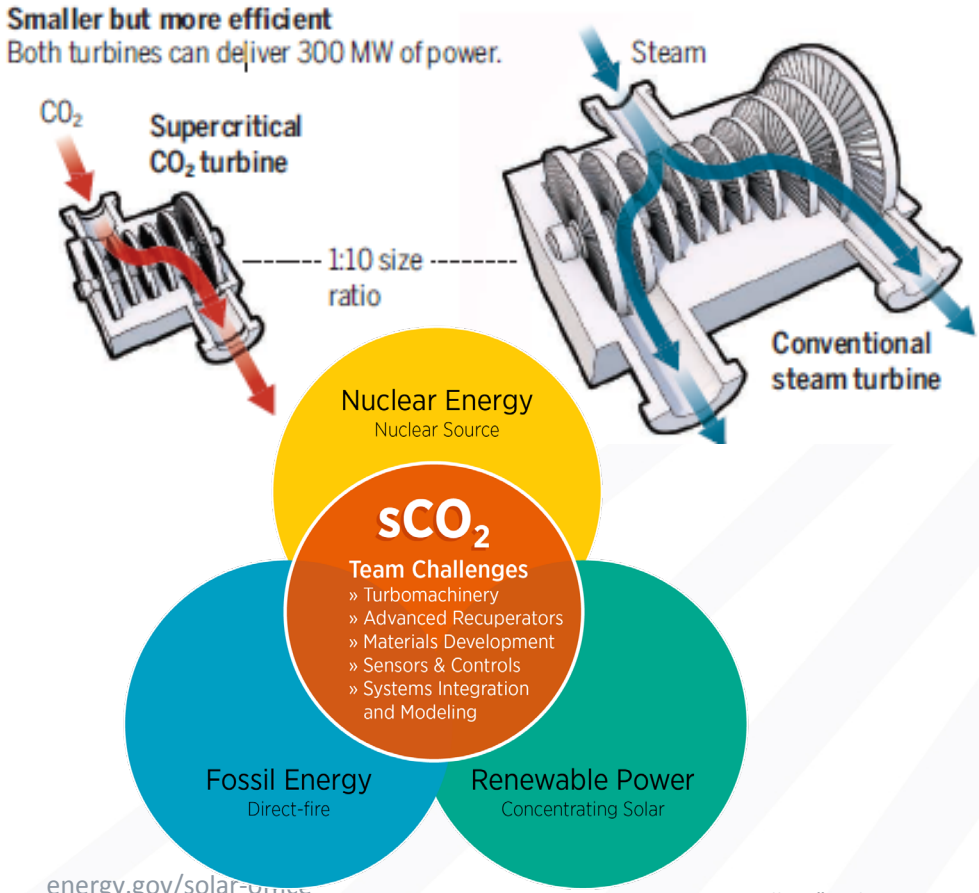
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

DOE Research and Development on sCO_2 Power Cycles

Dr. Avi Shultz
Program Manager
Solar Energy Technologies Office

DOE sCO_2 Workshop
October 31-November 1, 2019
National Renewable Energy Laboratory, Golden, Colorado

Next Generation CSP will Leverage Next Generation Power Cycles



Advantages of the sCO_2 Brayton Cycle:

- Higher Efficiency (*50% at TIT of 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)

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

Thermal Energy Storage + sCO_2 Power Cycles

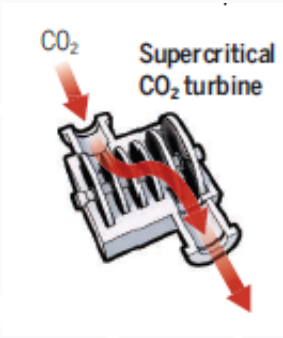
COAL

NUCLEAR

SOLAR THERMAL (CSP)

+

+



Thermal Resource Limitations:

- **Difficult to modulate** heat generation from nuclear fission
- Ramping coal boilers significantly **reduces lifetime**
- Solar thermal is a **variable energy resource**

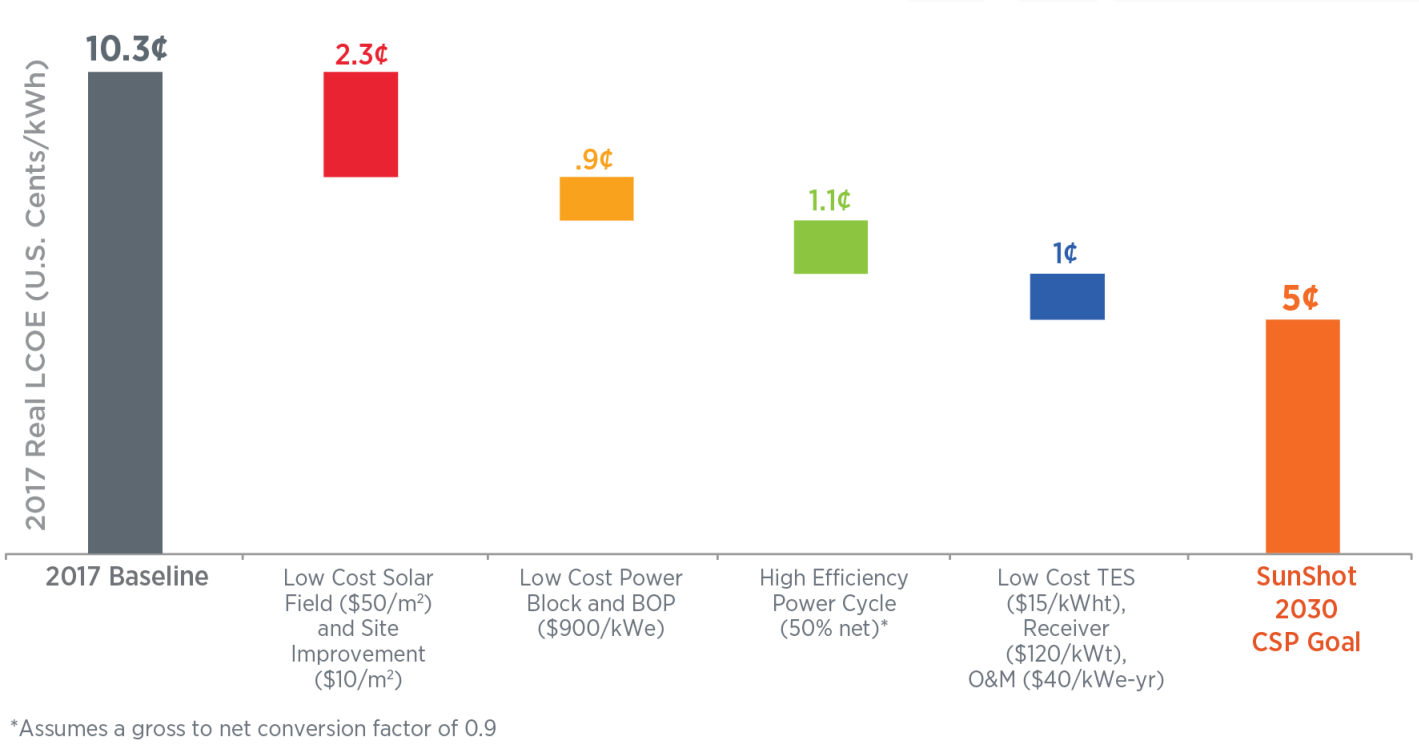
Thermal Energy Storage:

- **On-demand**, dispatchable energy generation
- **Increased reliability** due to buffering of variations in primary energy resource
- Technology readily scales to **long duration** (≥ 10 hours)

sCO_2 Power Cycles:

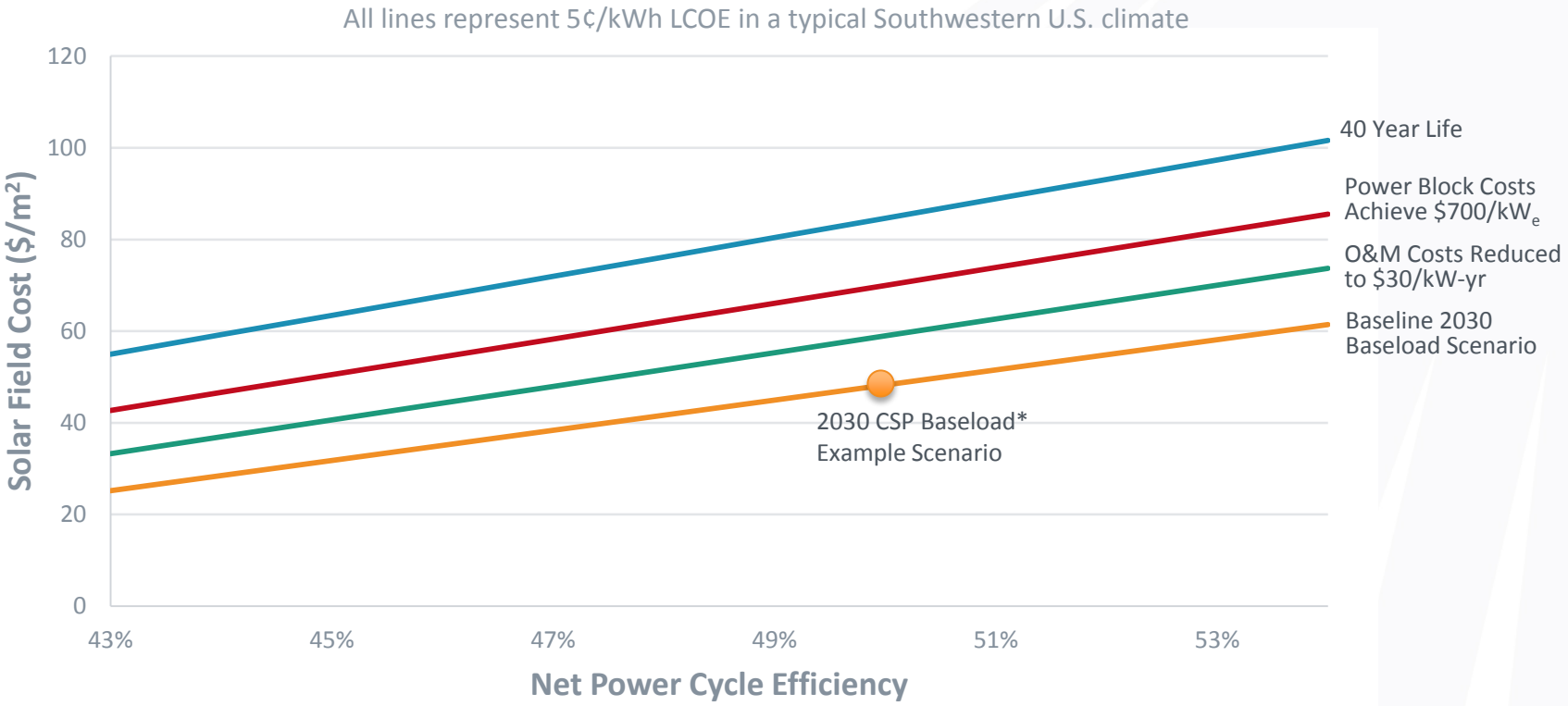
- Readily scalable to **< 100 MW** without significant loss in efficiency for **improved flexibility and siting**
- **Similar or higher efficiency** than steam cycles
- **Compact components** and **lower capital cost** for the same power output
- Much more amenable to **dry cooling** than conventional power cycles

A Pathway to 5 Cents per KWh for Baseload CSP



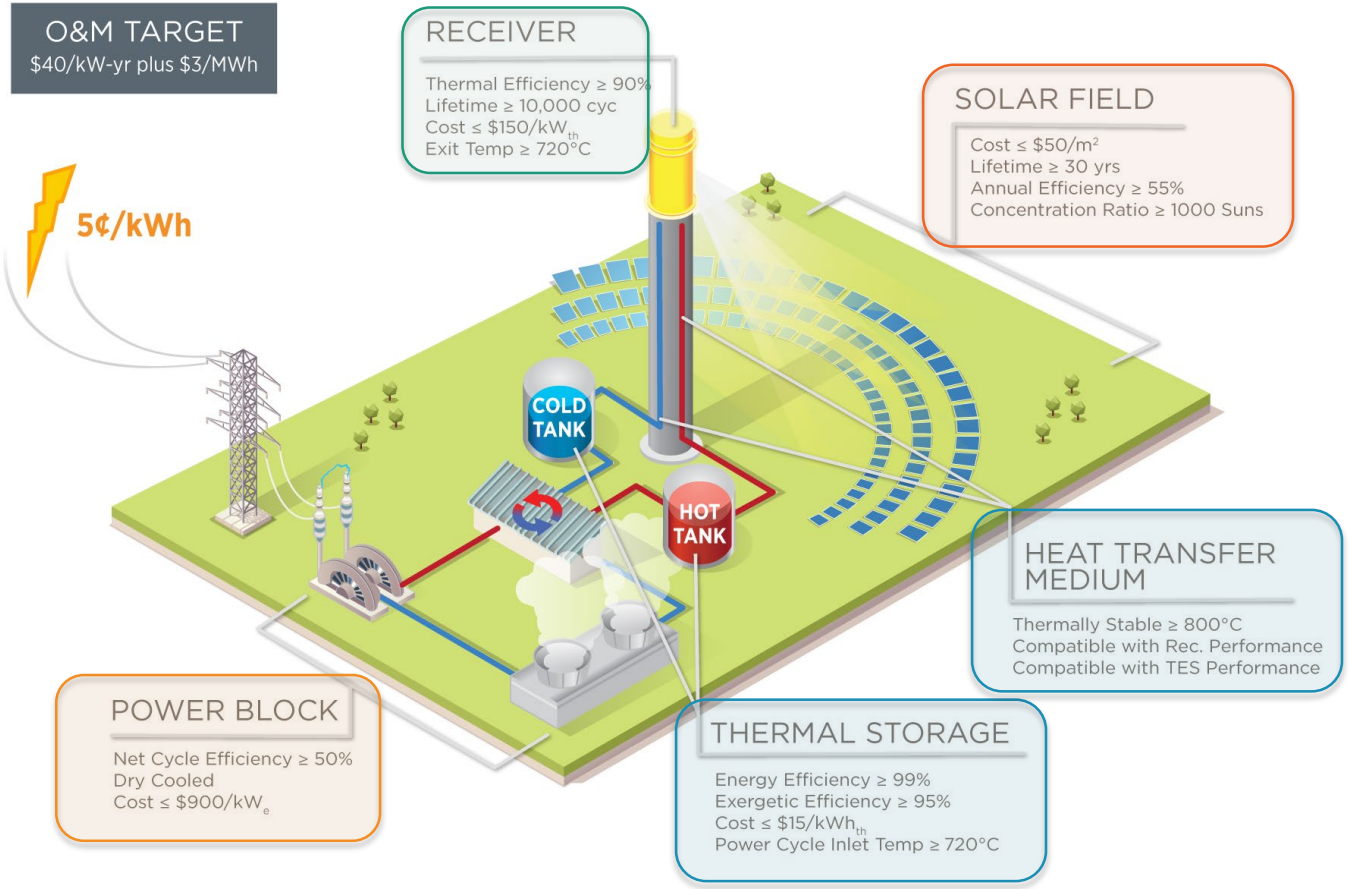
*Assumes a gross to net conversion factor of 0.9

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

CSP Program Technical Targets



Competitive Programs

$33M	FY19 SETO FOA (2019)
$22M	FY18 SETO FOA (2019)
$21M	Solar Desalination (2018)
$22M	FY19-21 National Lab Call (2018)
$70M	Gen3 CSP Systems (2018)
$15M	Gen3 CSP Lab Support (2018)
$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)

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	SwRI
	High-Temperature Dry-Gas Seal Development and Testing	SwRI
	Gas Lubricated Bearings for Drivetrain in sCO2 Cycle	GE
Materials	Fabrication and Application of High Temperature Ni-Based Alloys	EPRI
Other Components	Development and Testing of a Switched-Bed Regenerator	UW-Madison
	sCO_2 Power Cycle with Integrated Thermochemical Energy Storage	Echogen Power Systems
	Additively Manufacturing Recuperators via DMLM and Binder Jet Technology	GE
	Development of a High-Efficiency Hybrid Dry Cooler System	SwRI
Technoeconomics	Cycle Modeling, Integration with CSP, and Technoeconomics	NREL

Fossil Energy (FE) Collaboration in sCO2

Pilot Plants and pre-FEED Studies

- **$90.4 M** with partners GTI (STEP Project), GA Tech, Echogen, 8 Rivers, and Key Logic

Oxy Fuel Combustion for Direct Fired cycles

- **$9.3 M** with partners including SwRI, GA Tech., UCF, Combustion Research & Flow Tech., and Cascade Technology

Modular Hybrid Heat

- **$1.5 M** with partners SwRI, GA Tech., UCF, Combustion Research and Flow Tech. Inc, and Cascade Technology

Turbines, Recuperators, Materials Research

- **$19.3 M** with partners GE, Altex, Combustion Research and Flow Tech. Inc,Thar and ORNL

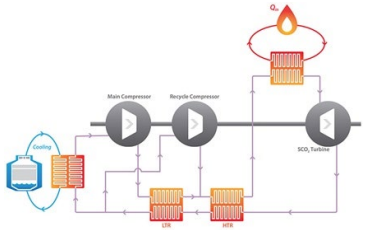
Leveraging investments in SCO2 power cycles to realize:

- **More efficient coal boilers,**
- **Power cycles optimized for carbon capture,**
- **Energy storage,**
- **Waste heat recovery, and**
- **Modular SCO2 power cycles**

Funding values represent total values for projects within the specified area

Coal FIRST (Flexible, Innovative, Resilient, Small, and Transformative)

- **Currently funding two projects at >$1M for pre-FEED studies.**
  - Supercritical CO2 Power Cycle Integrated with Energy Storage with (Echogen Inc. Systems
  - Direct-fired Supercritical Carbon Dioxide Power Cycle with 8 Rivers Capital
- **Pre-FEED with MI National Guard Fort Custer to provide 7.5 MW nominal size power plant**
  - Plant will provide reliable source to base and dispatch rest of power to Consumer Electric's grid in Michigan
  - Solar Inc. turbine with supercritical CO2 cycle to recover heat
  - Overall efficiency is expected to exceed 50%
- **National Lab Collaborations between NETL and other labs for**
  - Providing comprehensive systems integration packages that include "all-of-the-above" strategy
  - Renewable energy and base load generation integration



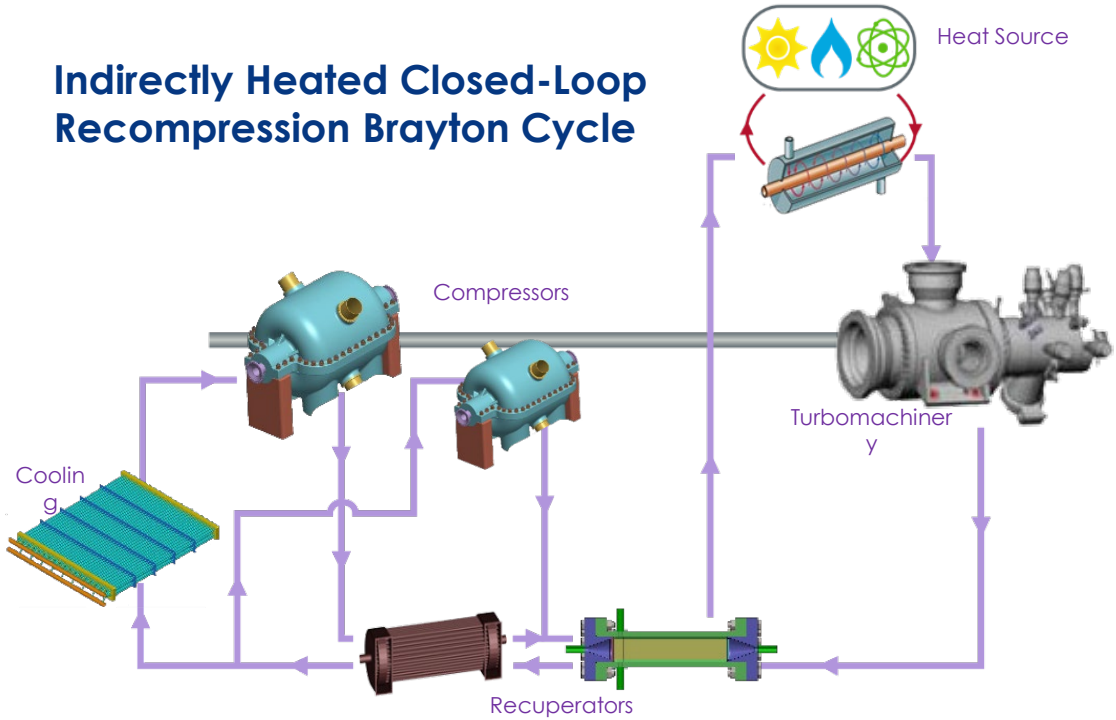
Source: NETL

DOE sCO_2 Crosscut Initiative: STEP Facility

10 MW_e STEP Pilot Facility

- Demonstrate models, controls, instrumentation, etc.
- Resolve issues common to multiple potential heat sources
- Facility Capabilities
  - Reconfigurable
  - 700°C operation
  - 300 bar
- Explore:
  - Operability
  - Cycle configuration
  - Component performance

Indirectly Heated Closed-Loop Recompression Brayton Cycle



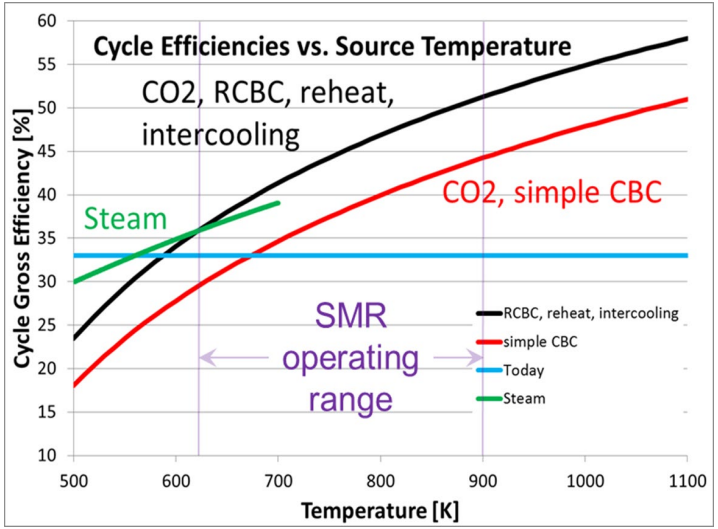
Project status: Major equipment on order; power cycle building under construction. Testing planned for 2021.

Office of Nuclear Energy - STEP R&D & Energy Conversion

- **STEP R&D Program**
  - Activities focused on reducing technology risk, and component development
  - Established 8 test configurations (Development Platforms):
    - 1 MWe Test Article, Heat Exchanger (SEARCH), Particle Imaging Velocimetry (PIV), Seals, Bearings, Turbcompressor (Core), Dry Heat Rejection (Tall Loop), Parallel Compression

- **ART Energy Conversion Team focuses on Sodium Fast Reactor Application**
  - Technology Roadmap/Project Management Plan/System Engineering Model completed
  - Commercialization of the sCO_2 system by 2030
  - Operating Recompression Closed Brayton Cycle (RCBC) at a turbine inlet of 550C (→ 700+C)
  - Development of Intermediate Sodium to CO_2 Heat Exchanger (Primary Heat Exchanger)
    - Sodium Drain, Fill, Plug in PCHE and Sodium/CO_2 interactions

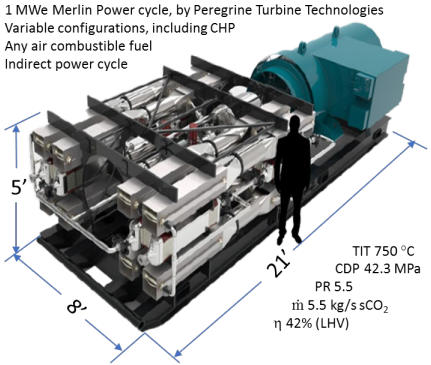
- **ART Engages Industry to Advance TRL of Components HTGR and MSR (550C & 750C)**
  - Federal Biz Ops (FBO) announcement to establish CRADA Lab & Industry collaborations



Technical Accomplishments

Turbomachinery

- 1 MWe Test article redesigned and initial testing completed
- Model and validation of turbo-machinery dry gas seals and hybrid gas bearings completed

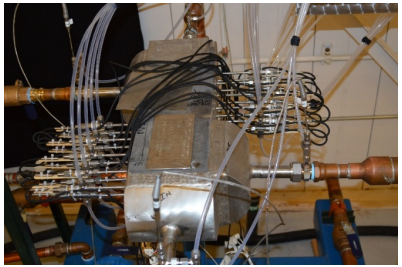


Systems Analysis & Integration

- Plant Dynamics Code (PDC) for sCO_2 developed; validation ongoing
- Testing and data from RCBC sCO_2 integrated recompression loop

Heat Exchangers

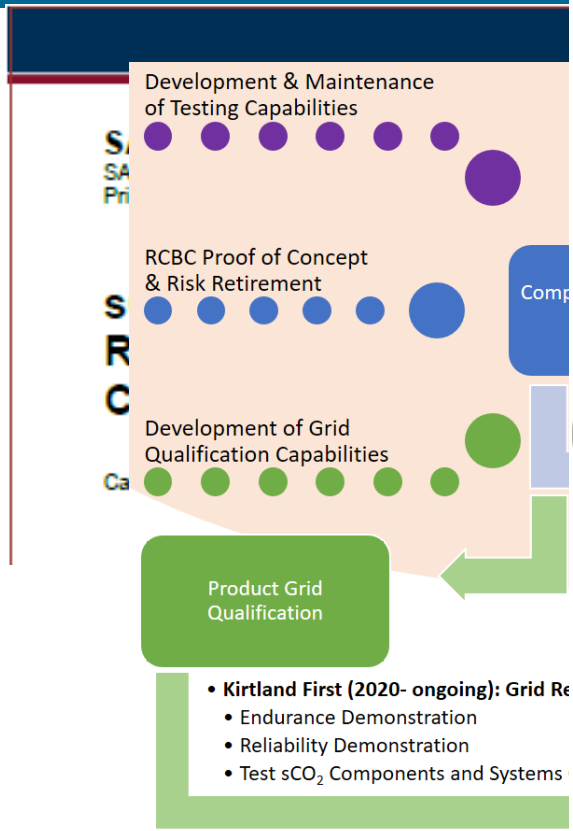
- ASME-qualified manufacture of diffusion-bonded, printed circuit heat exchangers

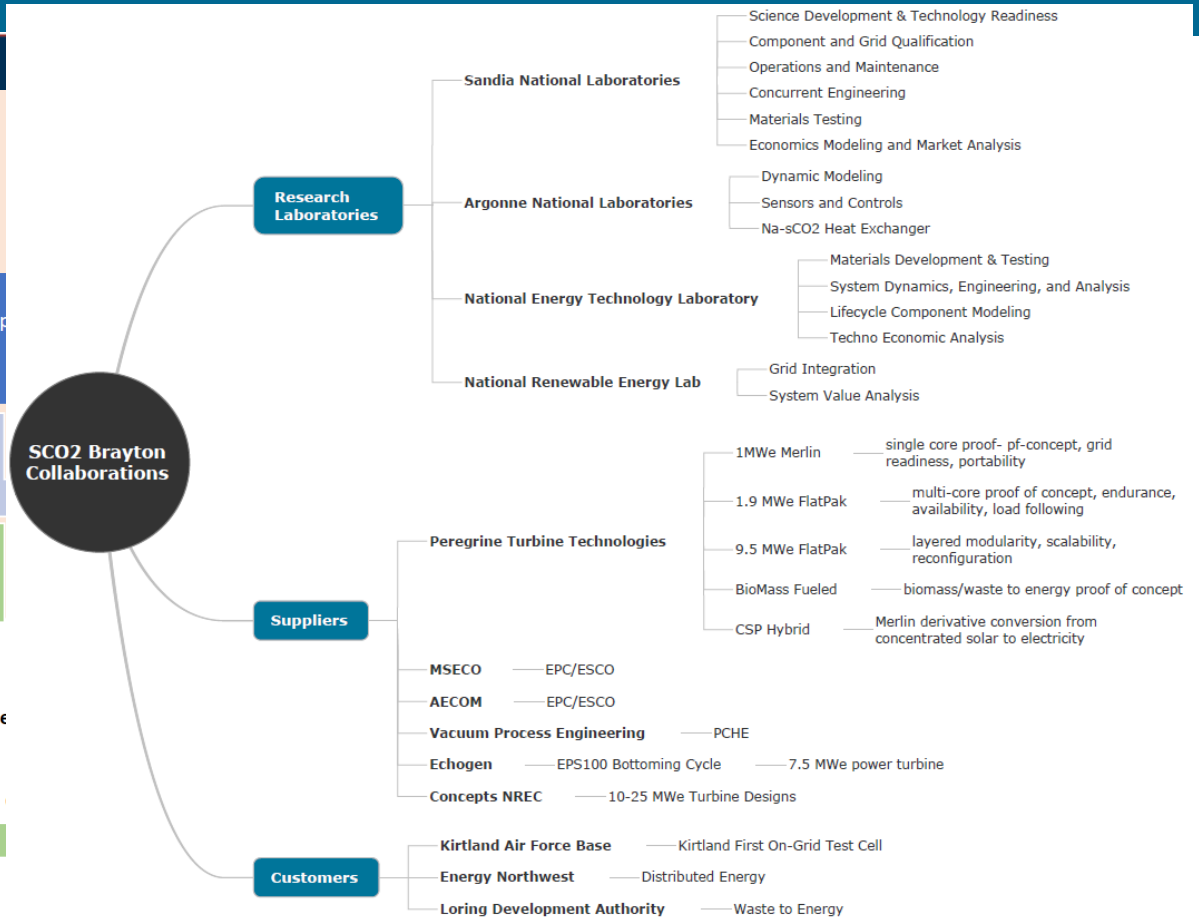


Materials

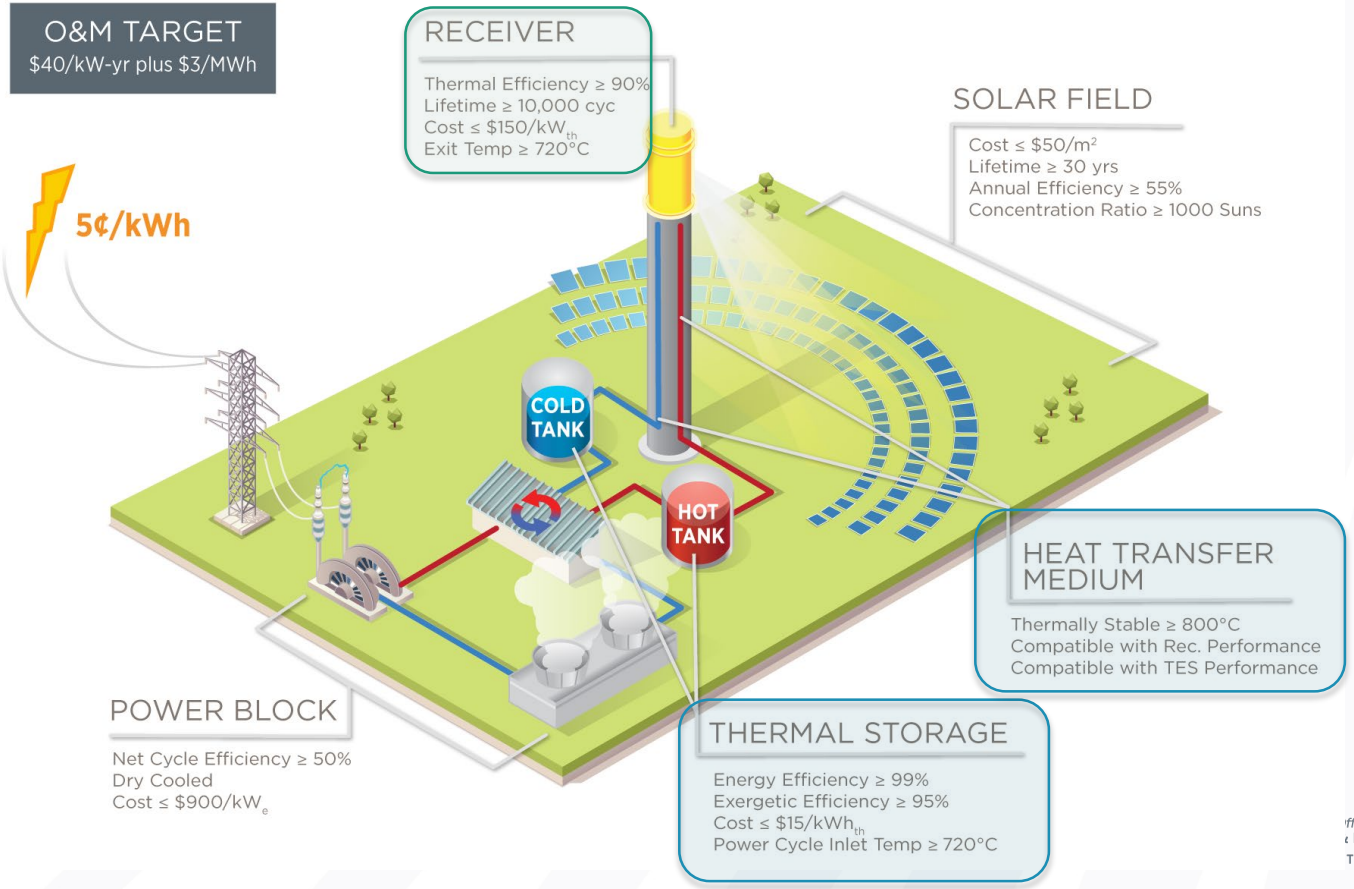
- Built high-temperature/pressure sCO_2 autoclaves at the SNL Materials Test Facility
- ASME Inconel 740 Code certification at 800 C for non-nuclear application
- Completed sCO_2 oxidation and corrosion tests for validation models
- Completed successful model for predictive impacts on corrosion, creep, and alloy fatigue life

Sandia – sCO_2 Roadmap for NE Applications

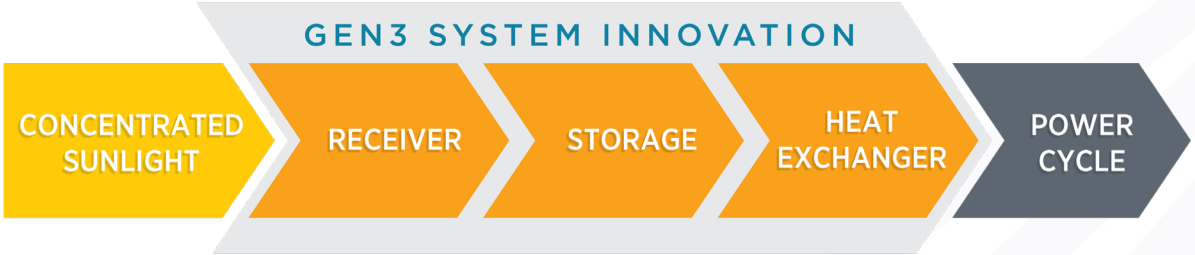


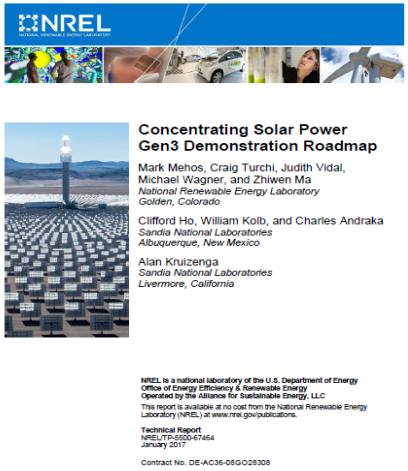


CSP Program Technical Targets



Gen3 CSP: Raising the Temperature of Solar Thermal Systems




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

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Livermore, California

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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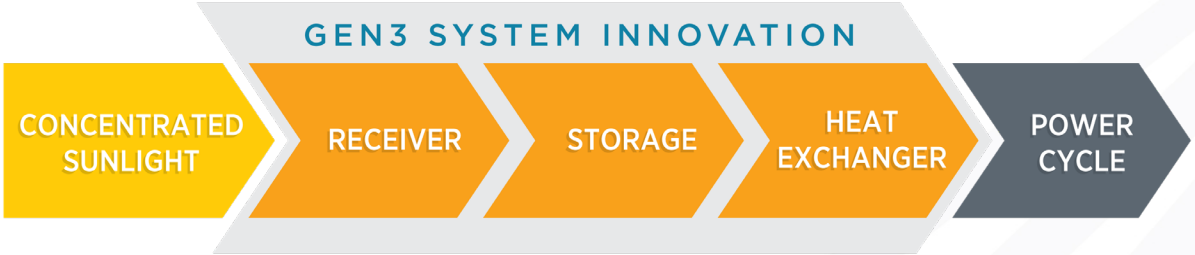
Technical Report
NREL/TP-5500-67464
January 2017

Contract No. DE-AC36-08GO28308

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

Gen3 CSP: Raising the Temperature of Solar Thermal Systems



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 Topic 1 Awardees

Sandia National Laboratories

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

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

DOE Award (P1-2): $8,067,661

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		

Questions?

Avi Shultz

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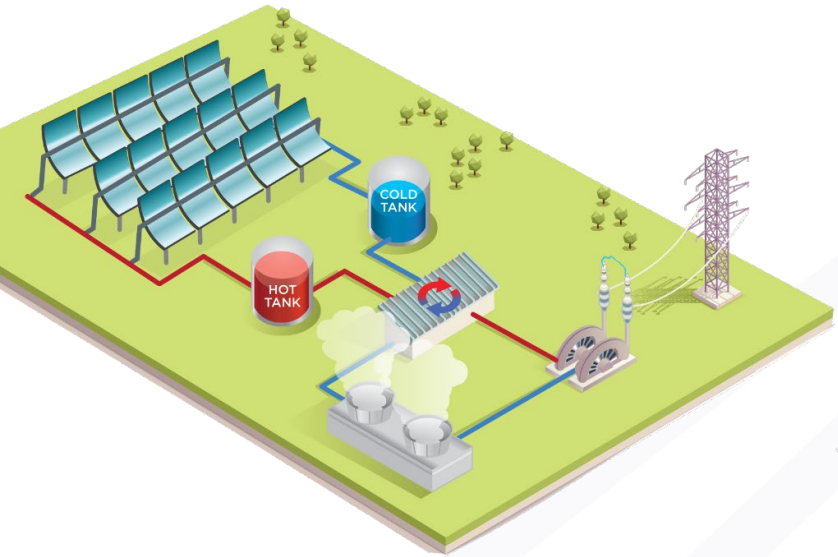
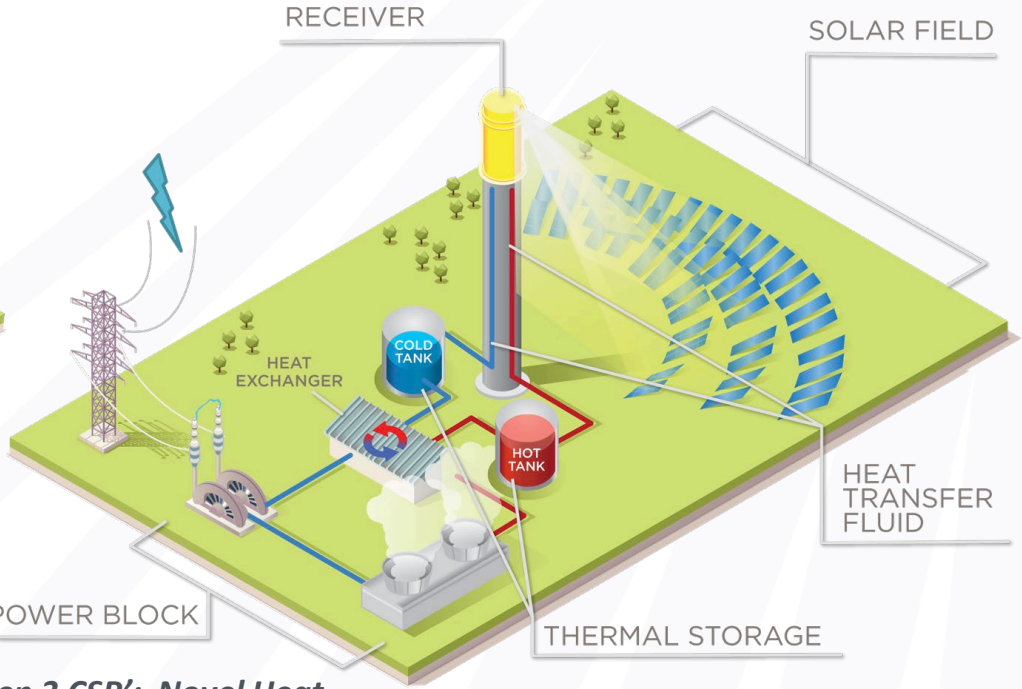
Program Manager, CSP
Solar Energy Technologies Office

CSP with Storage is Solar Energy On-Demand



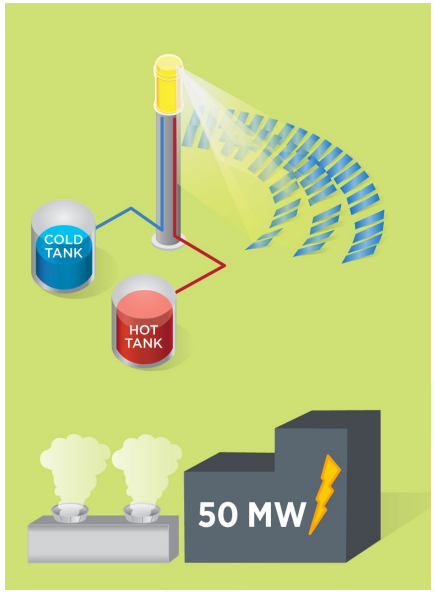


Oil-Based Troughs with steam rankine cycle (~400 °C) → ***Molten Salt Towers with steam rankine cycle (~565 °C)*** → ***'Gen 3 CSP': Novel Heat Transfer Media with advanced power cycle (>700 °C) @ 5¢/kWh***

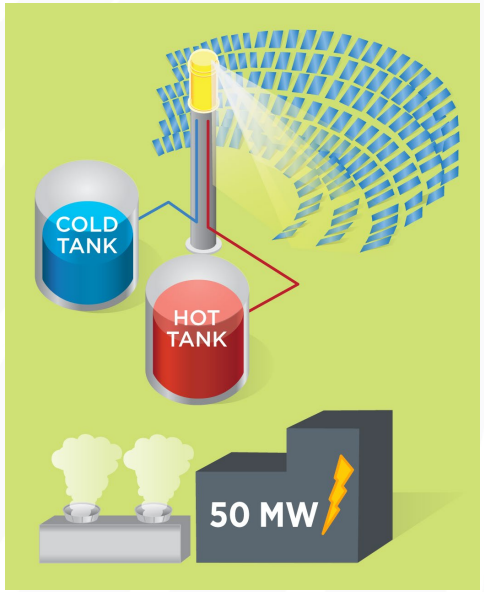
energy.gov/solar-office

CSP: Flexible Designs for an Evolving Grid

'Peaker'
(≤6 hours of storage)

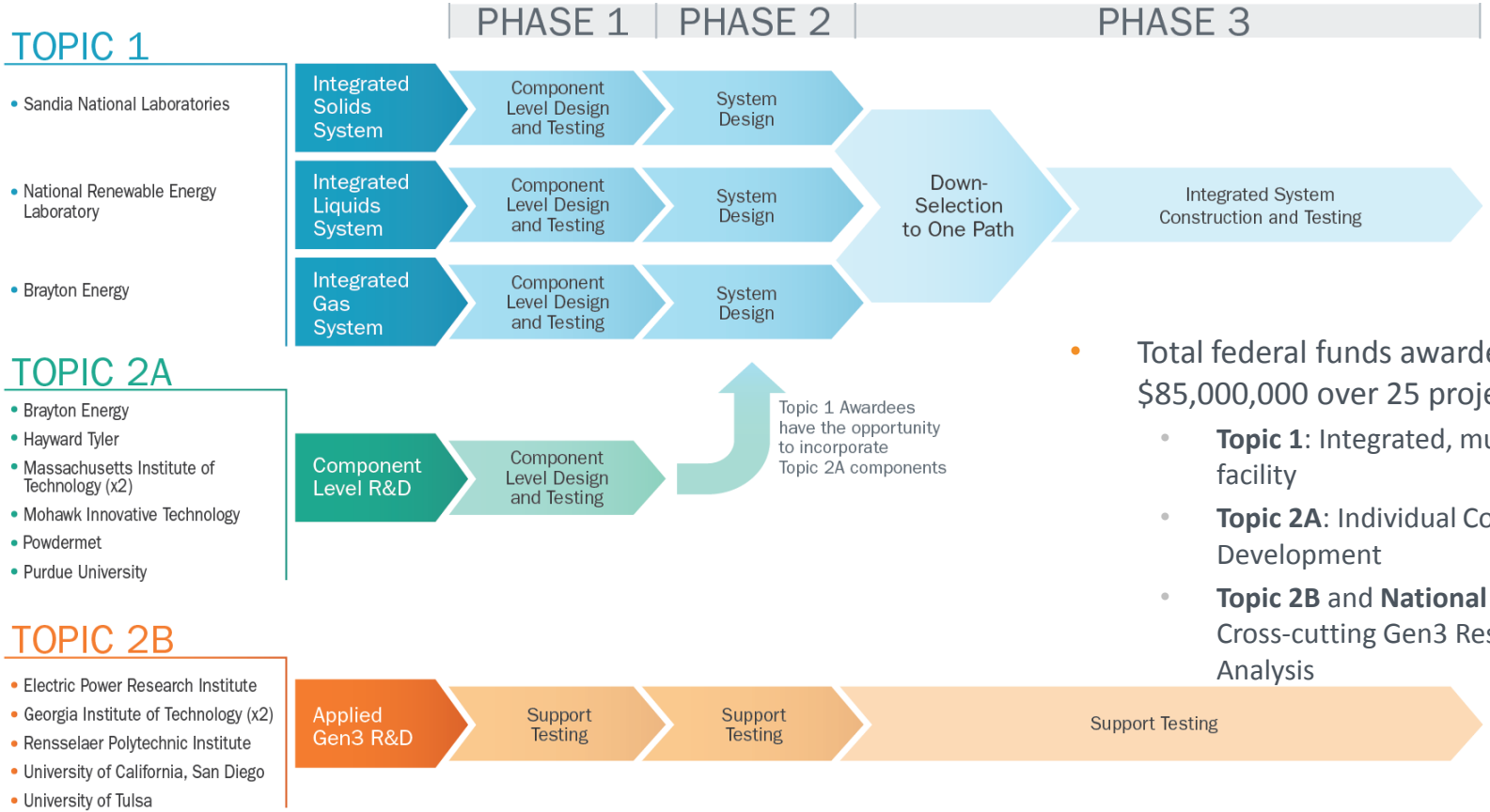


'Baseload'
(≥12 hours of storage)



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

Gen3 CSP Awardees



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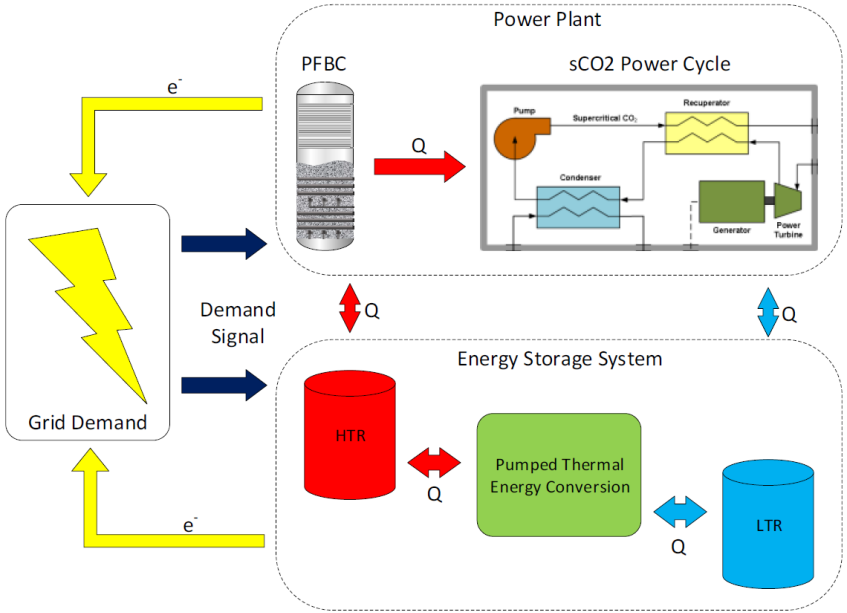
Coal FIRST Project:
Indirect Supercritical CO_2 Power Cycle Integrated with Energy Storage

Echogen Power Systems

- Advanced, modular coal combustion technology with high-efficiency sCO2 power block and combined electrical / thermal storage technology
- Air-fired PFBC based on DOE-funded oxy-PFBC project
- Recompression Brayton Cycle with potential for mid-temperature heat addition
- Turbine-driven compressors
- Electro-thermal energy storage-system charged by motor-driven heat pump cycle-System generates electricity by reversing process
- PFBC adaptable to oxy-combustion
- Air-fired PFBC compatible with post-combustion capture technologies



PFBC / sCO_2 / ETES plant concept

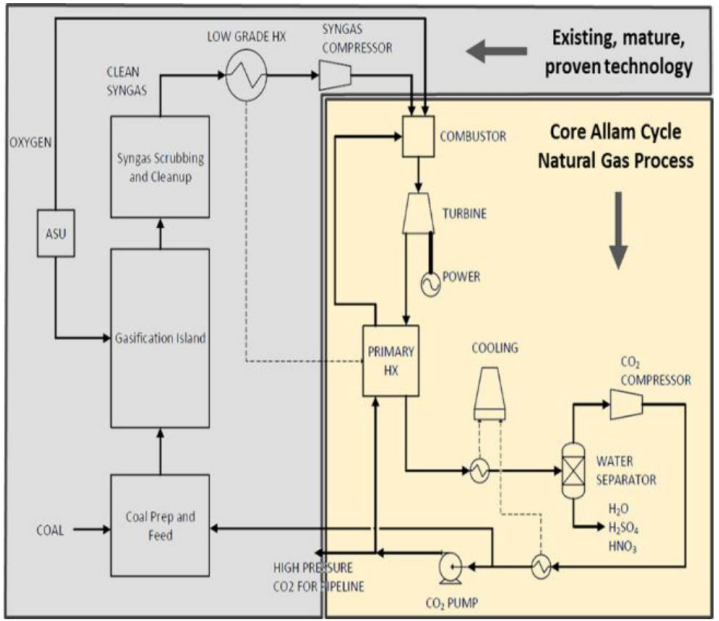
Team Members: Gas Technology Institute, EPRI, Louis Perry Group

89243319CFE000022, Echogen Power Systems (DE), Inc., Timothy J. Held, 234-542-4379 , theld@echogen.com

Coal FIRST Project:
Direct-fired Supercritical Carbon Dioxide Power Cycle

8 Rivers Capital LLC

- Coal syngas fired Allam cycle utilizing existing coal gasification technologies
- 294 MWe net, 43.3%–44.5% LHV net, low cost ($33/MWh), and near-zero emissions power generation cycle
- Economic estimates include significant value for CO_2 tax credit/sales ($41.5/MWh), Ar and N_2 sales ($26.5/MWh)
- Requires 40% capacity to remain economic
- Captures over 97% of CO_2 at pipeline pressure without additional equipment or energy
- Allam Cycle demonstrated at 50MWth scale (NG, La Porte)
- Ramp rate is TBD through pilot testing (La Porte)
- Liquid oxygen / syngas can be stored for increased flexibility
- Capable of natural gas co-firing



Allam cycle coal process integration

Team Members: WSP UK Limited, Gas Technology Institute

89243319CFE000015, 8 Rivers Capital, LLC, Adam Goff, 919-667-1800, adam.goff@8Rivers.com

sCO_2 Power Cycles Projects – Fossil Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

Oxy Fuel Combustion that will help FE realize the potential for Direct Fired Cycles

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion	**Southwest Research Institute**	Oxy-Fuel Combustion	10/1/2014	**4,579,719**
Investigation of Autoignition and Combustion Stability of High Pressure Supercritical Carbon Dioxide Oxycombustion	**Georgia Tech Research Corporation**	Oxy-Fuel Combustion	10/1/2015	**880,498**
Chemical Kinetic Modeling Development and Validation Experiments for Direct Fired Supercritical Carbon Dioxide Combustor	**University of Central Florida**	Oxy-Fuel Combustion	10/1/2015	**1,026,974**
Development of Oxy-Fuel Combustion Turbines with CO_2 Dilution for sCO_2-Based Power Cycles	**Southwest Research Institute**	Oxy-Fuel Combustion Turbine	7/9/2018	**500,000**
Combustion Modeling for Direct Fired Supercritical CO2 Power Cycles	**Combustion Research and Flow Technology Inc.**	Combustion modeling	2/21/2017	**1,152,799**
Highly Scalable Large-Eddy Simulations of Oxy-Fuel Combustors for Direct-Fired Supercritical CO2 Power	**Cascade Technologies, Inc.**	Combustion modeling	2/21/2017	**1,154,173**

sCO_2 Power Cycles Projects – Fossil Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

Turbines

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide (SCO2) Turbo Expanders	**General Electric**	Turbomachinery	10/1/2014	**6,824,098**
Simulation Tool for Turbomachinery Operating with Trans-Critical Real Fluids	**Combustion Research and Flow Technology Inc.**	Modeling	6/13/2016	**1,149,998**

Modular Hybrid Heat Engines

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
Integrated Optimization and Control of a Hybrid Gas Turbine/sCO_2 Power System	**Echogen Power Systems**	Modular Hybrid Heat Engines	7/9/2018	**500,000**
Novel Modular Heat Engines with sCO_2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery	**General Electric**	Modular Hybrid Heat Engines	7/9/2018	**499,757**
Advanced Gas Turbine and sCO_2 Combined Power Cycle Power System	**Southwest Research Institute**	Modular Hybrid Heat Engines	7/9/2018	**500,000**

sCO_2 Power Cycles Projects – Fossil Energy

Pilot Plants and pre-FEED Studies

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
Supercritical Carbon Dioxide Primary Power Large-Scale Pilot Plant	**Echogen Power Systems**	Large-scale coal-fired pilot	4/1/2018	**3,239,879**
Supercritical Carbon Dioxide Pilot Plant Test Facility	**Gas Technology Institute**	STEP 10 MWe Pilot Facility	10/1/2016	**84,330,971**
Coal-Based Power Plants of the Future	**Echogen Power Systems**	Pre-FEED study for indirect sCO2 coal-fueled air-fired power plant with energy storage and CO2 capture	4/15/2019	**1,241,696**
Coal-Based Power Plants of the Future	**8 Rivers Capital**	Pre-FEED study for direct sCO2 coal-fueled power plant	4/15/2019	**1,143,086**
Fort Custer sCO2 Power Plant Study	**Team KeyLogic**	Pre-FEED study for 5 MW combustion turbine and 2.5 MW sCO2 cycle power plant	4/26/2019	**432,908**

sCO_2 Power Cycles Projects – Fossil Energy

NATIONAL ENERGY TECHNOLOGY LABORATORY

Recuperators

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
Technology Development of Modular, Low-Cost, High-Temperature Recuperators for SCO2 Power Cycles	Thar Energy	Recuperators	10/1/2015	**9,344,826**
Corrosion and Erosion Resistant Surface Features for High Pressure Supercritical Carbon Dioxide Heat Exchangers	Altex Technologies	Surface Features for Heat Exchangers	2/22/2016	**1,148,125**

Materials

Project Title	Performer	Scope	Project Start Date	DOE Funding ($)
Properties of Advanced Ni-Based Alloys for A-USC Steam Turbines	ORNL	Materials	2/1/2016	**150,000**
Advanced Materials Issues in Supercritical Carbon Dioxide	Oak Ridge National Lab	Materials	10/1/2015	**650,000**