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

SOLAR ENERGY TECHNOLOGIES OFFICE

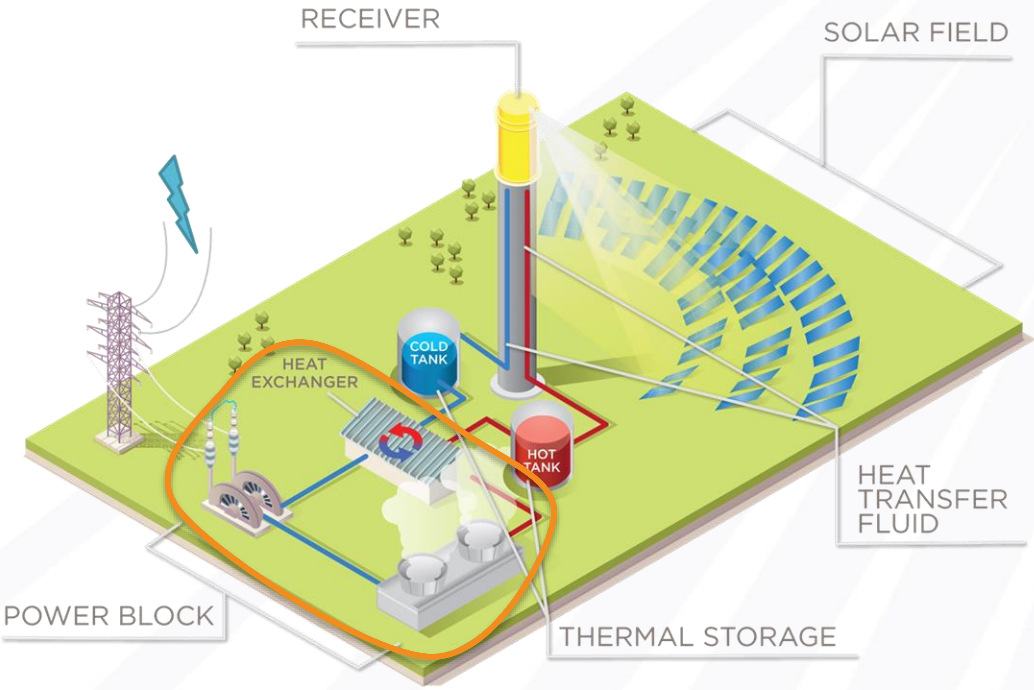
2020 SETO PEER REVIEW

Power Cycles: Supercritical CO2 Brayton Cycle Development Overview

SETO 2020 Peer Review

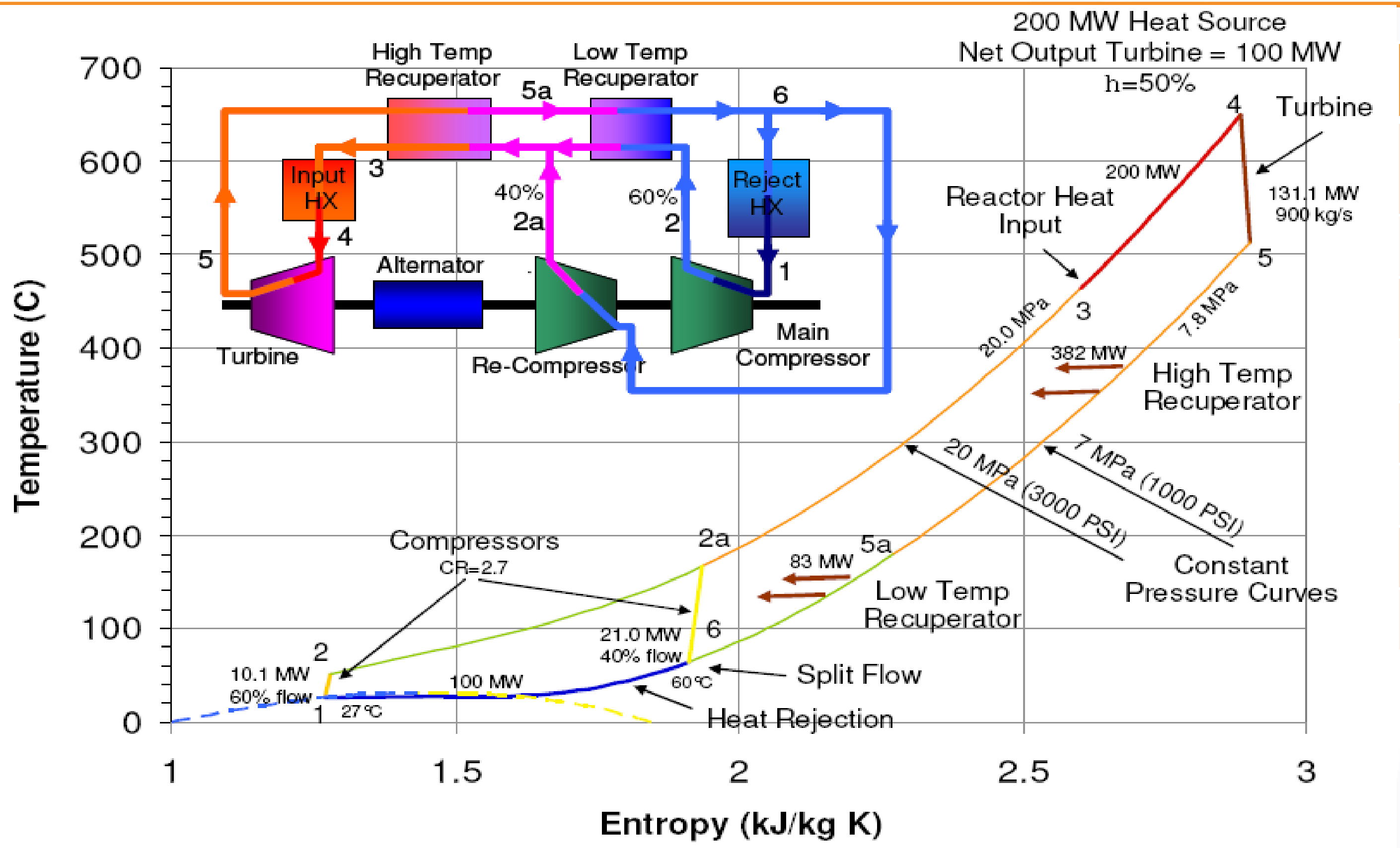
Rajgopal Vijaykumar, Technology Manager

sCO_2 Power Block in a CSP Plant (Where)



Target: 50% Efficiency at 715°C turbine inlet temperature at 900 $/kWE, air cooling

What is a sCO_2 Power Cycle?



- **Turbomachinery**
  - Compressors (MC and RC)
  - Expander (T)
- **Recuperator**
  - HTR
  - LTR
- **Heat Exchangers**
  - PHX
  - Cooler

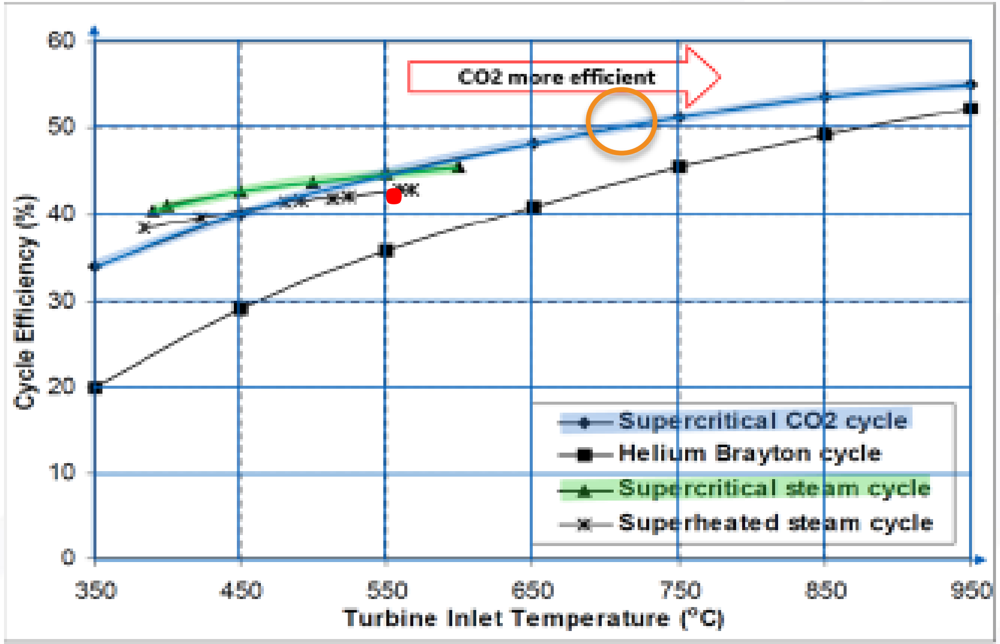
Why sCO_2 Power Cycle for CSP?

- Higher cycle efficiency than the Rankine Cycle for a given Heat Transfer Fluid (HTF) outlet temperature
- Ability to interface better with the high temperature HTF at smaller scale, as supercritical Rankine cycle systems have not been built at 100 MW_e scale and less
- Compactness; Ease of build, installation and operation (especially for higher temperatures)
- Ability to incorporate air cooling as ultimate heat sink, with small impact on cycle efficiency
- Potential to reduce the cost and LCOE
  - NETL Study suggests 50-100 Me power block can possibly achieve 900 $/kWe
  - Operational simplicity compared to steam cycle that can possibly lead to reduced O&M cost

Why sCO2 Power Cycles for CSP

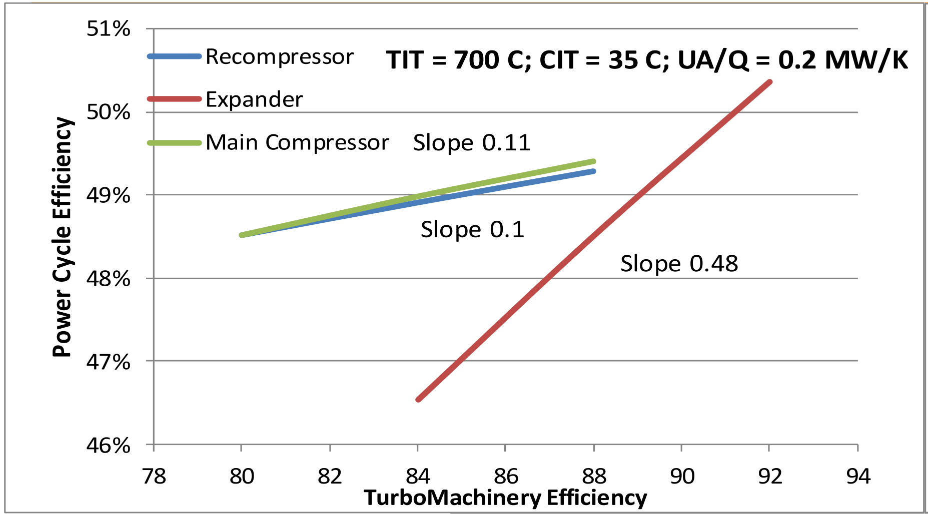
Gen3

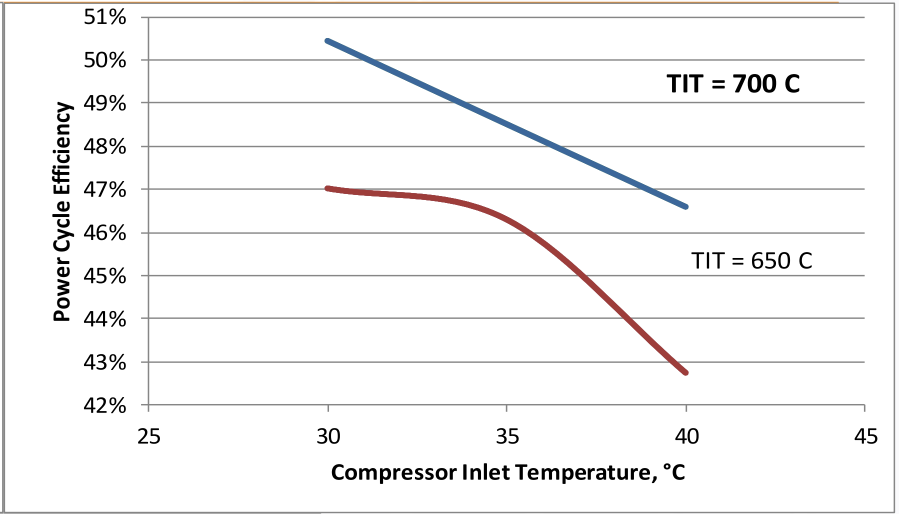
Gen2

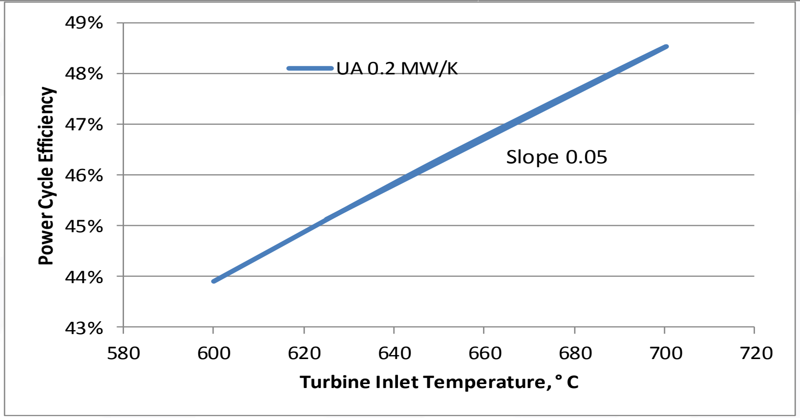


More efficient than steam cycle in 540-750°C Turbine Inlet Temperature

Higher TIT, Turbomachinery efficiency for higher cycle η







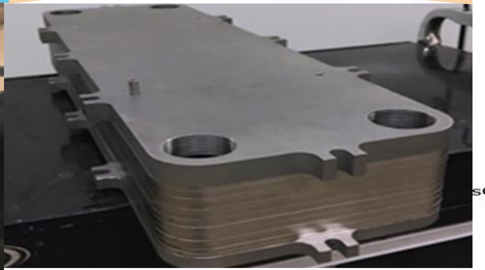
EERE sCO_2 Technology Program

- *>$55 M investment since 2012*

Turbomachinery

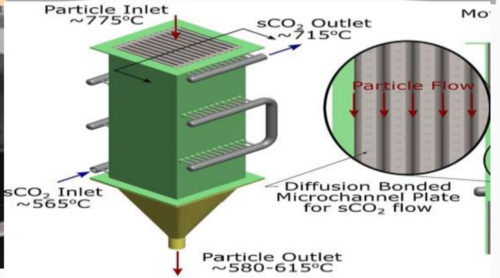
- Develop turbomachinery for the high sCO_2 density and high temperatures and pressures of the cycle
- $22 M

Recuperators



- Design, build and test recuperators for recovering energy in the sCO_2 Cycles
- >$5 M

Heat Exchangers and Coolers



- Develop high pressure/high temperature heat exchangers for energy input and air cooled precoolers
- $14.5M

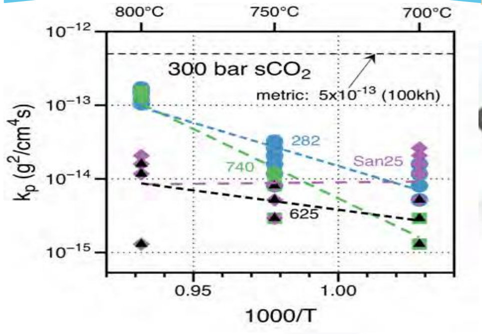
STEP Support Integrated TESTBED

- Compressor, Expander and LTR Scaled up from SETO Research
- Integrate sCO2 cycle with Thermal Energy Storage at more nominal operating temperatures

EERE sCO_2 Technology Program

- *>$55 M investment since 2012*

Fundamental Research

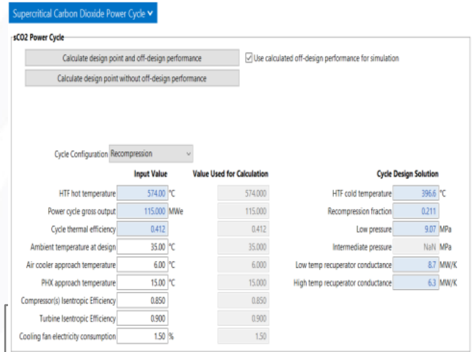


- Understanding of corrosion, lifetime of components
- $4M

SubComponents and Manufacturing

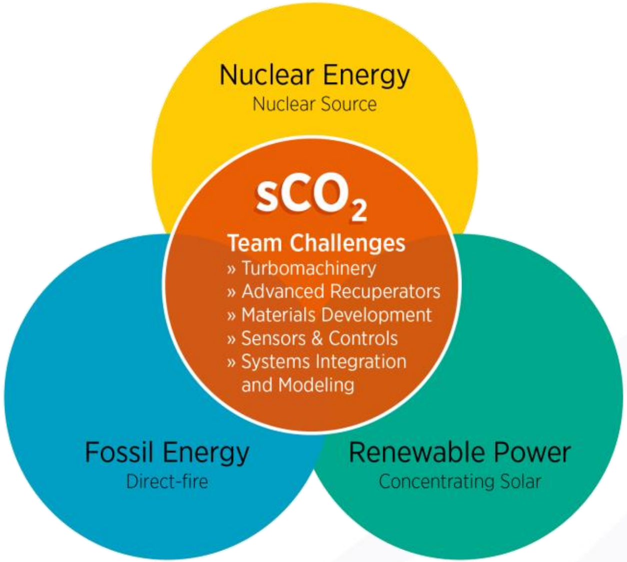
- Design subcomponents to improve turbomachinery efficiency and performance; improve manufacturing
- $9 M

Systems Integration & Optimization



- System analyses to design and integrate the sCO_2 power cycle with SAM for optimized performance, efficiency, cost, and operability when integrated with CSP

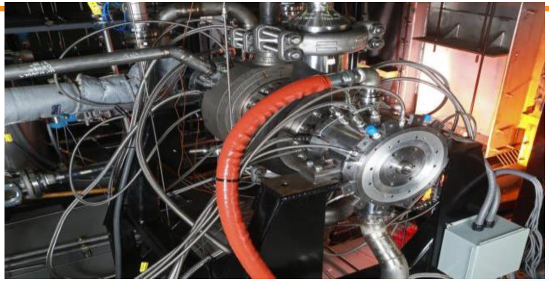
sCO2 Cross-Cut Program EE, NE and FE



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

A PATH TOWARDS TESTING A 10 MWe sCO_2 RCBC



DE-EE0005804 SUNSHOT EXPANDER	VPE Recuperator	Apollo Compressor	Dry Gas Seal Testing	STEP FACILITY
January 2019	January 2019	Summer 2020	Summer 2020	2021-2023

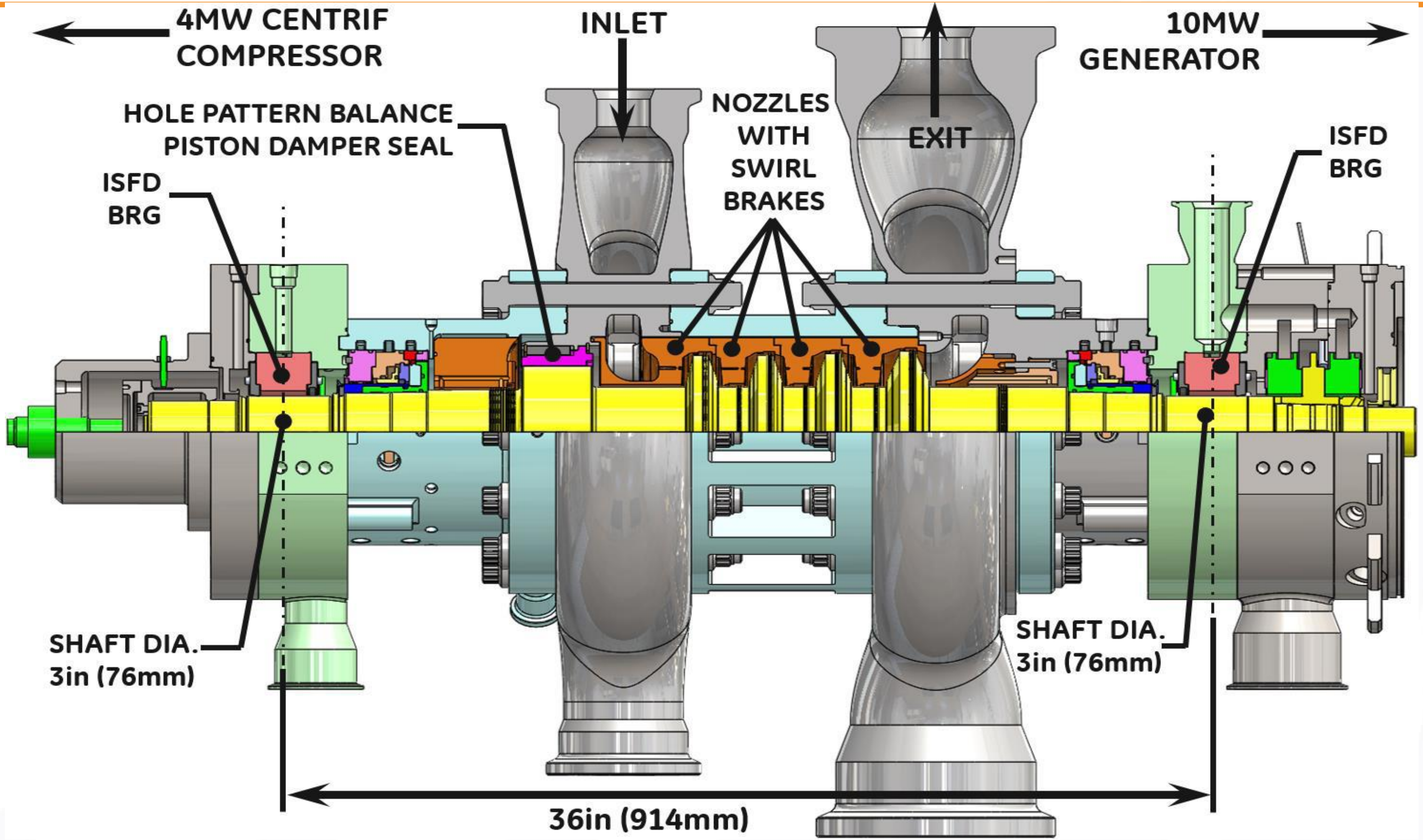
FROM SUNSHOT TO APOLLO TO STEP

SCO2 Turbomachinery

>$22 M investment since 2012

	Project Title	Performer	Description
Completed	Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO2 Operation	SWRI/GE/THAR	10 Mwe axial expander operated in a 5 MWth sCO_2 loop for~1 MWe output
In testing	Compression System Design and Testing for sCO2 CSP Operation	GE/SWRI	Compressor/recompressor at ~2 MWe input
In testing	Development of an Integrally Geared Compressor-Expander for SCO2 Brayton Cycle Power Generation Applications	Hanwha/SWRI	Integrally Geared all radial sCO_2 Compander (compressor and expander)
Started	Advanced compressors for CO2-based power cycles and energy storage systems	Echogen/UC/UND	Axial Compressor
In Progress	Oil-Free, High Temperature Heat Transfer Fluid Circulator	MTI	sCO_2 circulator ~1.5 MWth

SunShot Expander:- GE AND SWRI



Near Term sCO_2 Turbomachinery Research Needs

- Improvements in Expander Design
  - Reduce expander leakage
  - Improvements in dry gas seal thermal performance
  - Increase expander efficiency; Elimination of lube oil
  - Improvements in Bearing Rotor Dynamic Performance
- Improvements in Compressor Efficiency, Reduction in Compression Power
  - Improvement in dry gas seal performance
  - Broad range compressor performance, especially near dome
  - Axial Compressor design
- Improvements in Manufacturing
  - Casting or Novel Manufacturing Processes for casing
  - 3D printing or other Novel manufacturing for blades, rotor and bearings
- Improvements in Integration
  - Integration of compressor and expander into one single casing, drive train; elimination of seals

Recuperators

>$5 M investment since 2012

Status	Project Title	Performer	Description
Completed	Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO2 Operation	VPE	~5 MWth Recuperator
Completed	Advanced Supercritical Carbon Dioxide Cycles	UWisconsin	Packed bed regenerators as replacement of recuperators
In Progress	740H Diffusion Bonded Compact Heat Exchanger for High Temperature and Pressure Applications	COMPREX	diffusion-bonded heat exchanger using 740H
In Progress	Additively Manufactured sCO2 Power Cycle Heat Exchangers for CSP	General Electric	Binderjet manufacturing processes and heat exchanger core designs

Recuperator:- VPE at SWRI Compander facility

Robust in operation, but less than optimal effectiveness (~80%, 92% target)

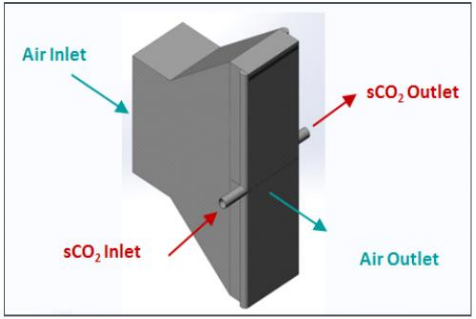
Additively Manufactured Heat Exchangers: GE

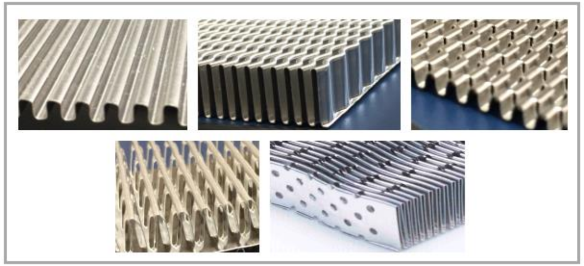
Primary Heat Exchangers and Precoolers

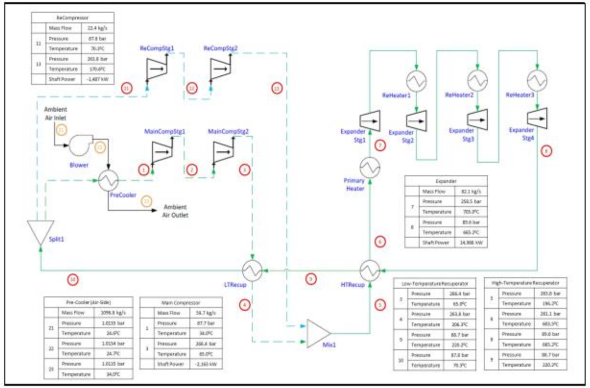
>$15 M investment since 2012

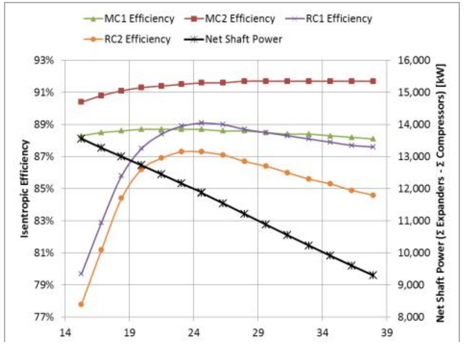
Status	Project Title	Performer	Description
Completed	Robust, Cost-Effective Heat Exchangers for 800°C Operation with Supercritical CO_2	Purdue	Compact millichanneled HEXs comprised of metal-coated ZrC/W-based cermets (ceramic/metal composites)
In Progress	Development of a High-Efficiency Hybrid Dry Cooler System for sCO_2 Power Cycles in CSP Applications	SWRI/VPE	Hybrid (microchanneled on sCO_2 side and finned on air side) cooler
Testing	High-Temperature Particle Heat Exchanger for sCO2 Power Cycles	SNL with SOLEX/VPE	particle/sCO2 heat exchanger operating at temperatures ≥ 720 °C and sCO2 pressures up to 20 MPa
In Progress	Additively-Manufactured Molten salt-to-supercritical Carbon Dioxide Heat Exchanger	UC Davis with CMU	molten salt-to-sCO_2 heat exchangers using additive manufacturing of nickel superalloys
In Progress	Low-Cost High Temperature Ceramic Heat Exchangers	ANL/OAI	ceramic based materials (SiC) with additive manufacturing technologies (Binderjet and heat treatment)

“Hybrid” Air PreCooler:- SWRI with VPE









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U.S. Department Of Energy

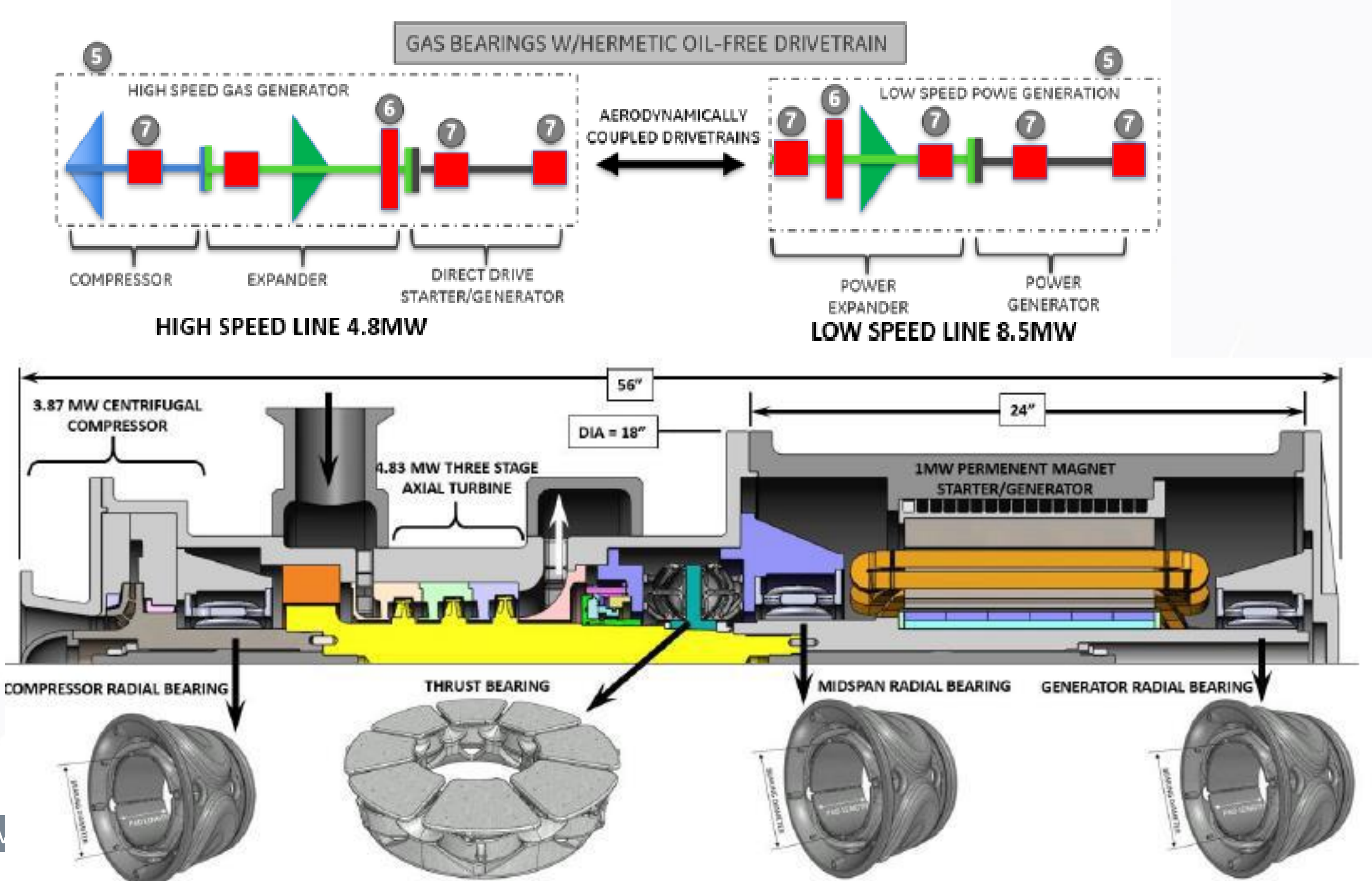
Turbomachinery SubComponents and Manufacturing

>$7.75 M investment since 2012

In Progress
In Progress
Started
In Progress
Started

Project Title	Performer	Description
Reduced LCoE CSP Through Utilizing Process Gas Lubricated Bearings in Oil-Free Drivetrains	GE	Process lubricated gas bearings; a conceptual rotor train layout using gas bearings.
High-Temperature Dry-Gas Seal Development and Testing for sCO2 Power Cycle Turbomachinery	SWRI/EB	a high-temperature dry-gas seal (DGS) for (500 °C) application to sCO2 power turbines.
Near-Net-Shape (NNS) Hot Isostatic Press (HIP) Manufacturing Modality for sCO2 CSP Capital Cost Reduction	GE	powder metallurgy based near-net-shape (NNS) hot isostatic pressed (HIP) HA282 components
Cast Components for High Temperature CSP Thermal Systems	ORNL	cast components, valves with cast valve bodies, and turbine casings using Haynes®282.
Vertically-Aligned Carbon Nanotube Arrays as Novel Self-Lubricating High-Efficiency Brush Seal for CSP Turbomachinery	ORNL	Novel brush seals for turbomachinery

Process Gas Lubricated Bearings:- General Electric

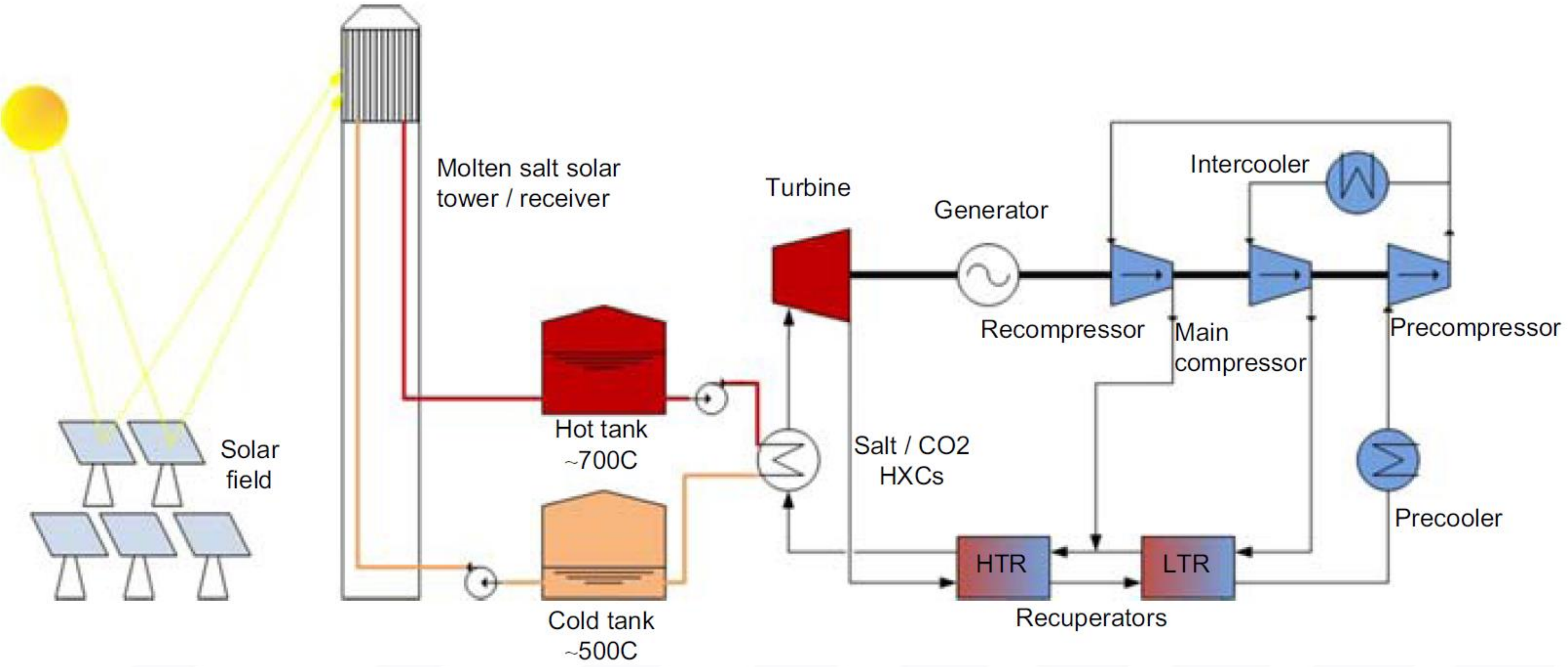


Fundamental Research for sCO_2

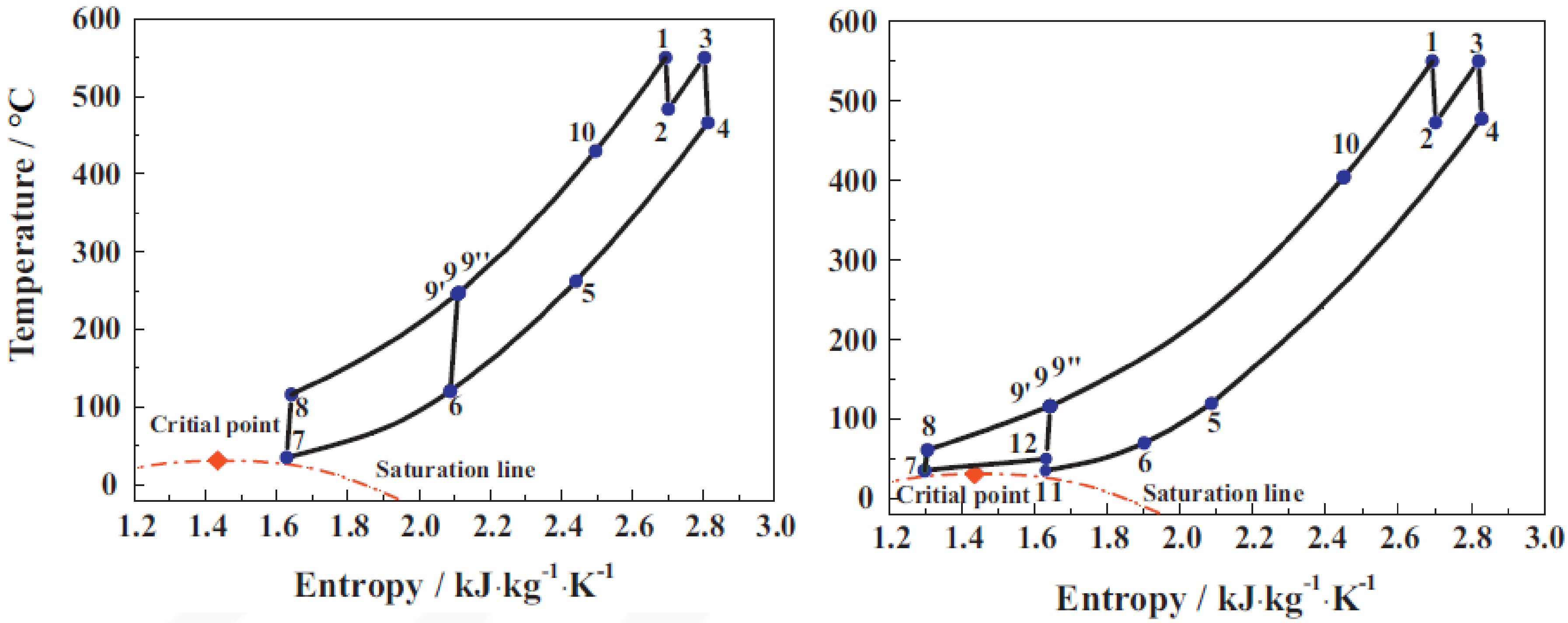
>$4 M investment since 2012

Status	Project Title	Performer	Description
Completed	Lifetime Model Development for Supercritical CO2 CSP Systems	ORNL	sCO_2 corrosion data and lifetime prediction
Completed	Physics-Based Reliability Models for Supercritical-CO2 Turbomachinery Components	GE	life prediction and reliability model of a hybrid gas bearing and a dry gas
Completed	Advanced Supercritical Carbon Dioxide Cycles	UWisconsin	Welded samples of high nickel alloys corrosion and strength testing
In Progress	CSP ANALYSES	NREL	Integrating sCO2 cycle analyses with CSP for SAM Computer Code

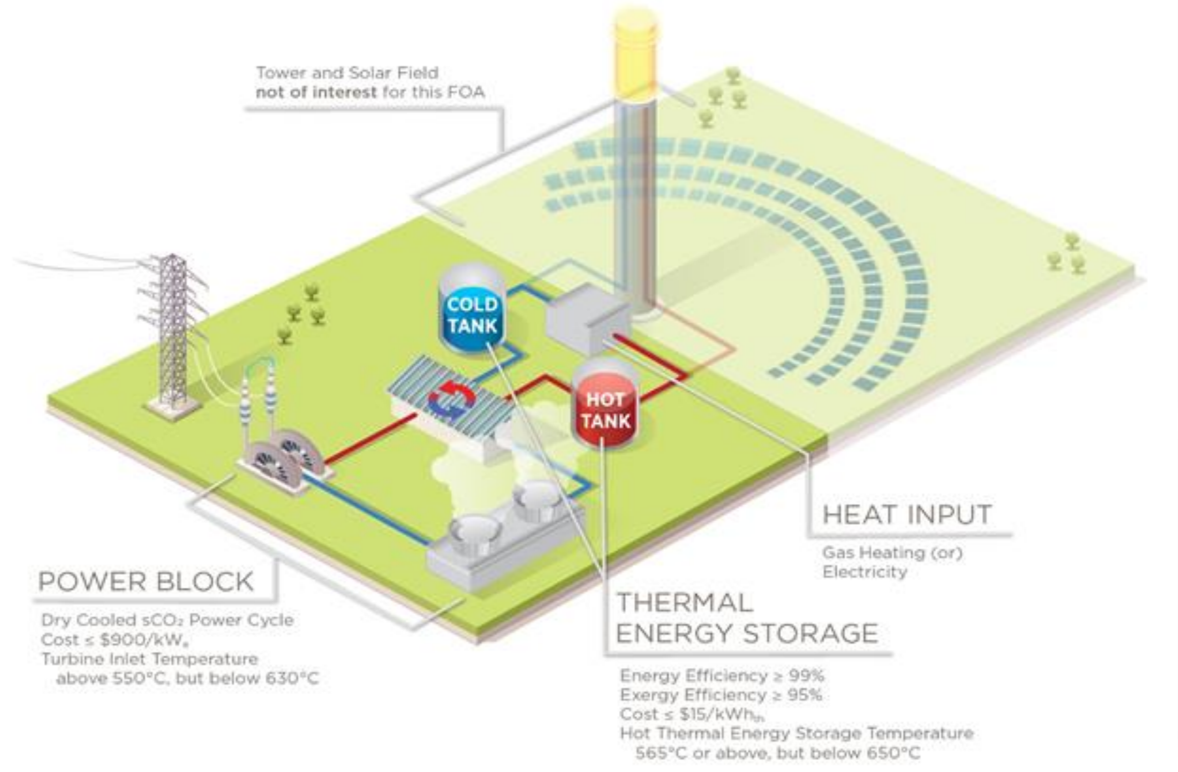
A new Cycle for CSP (NREL SAM Analyses)



A Cycle to Accommodate a Broader ΔT Across the TES

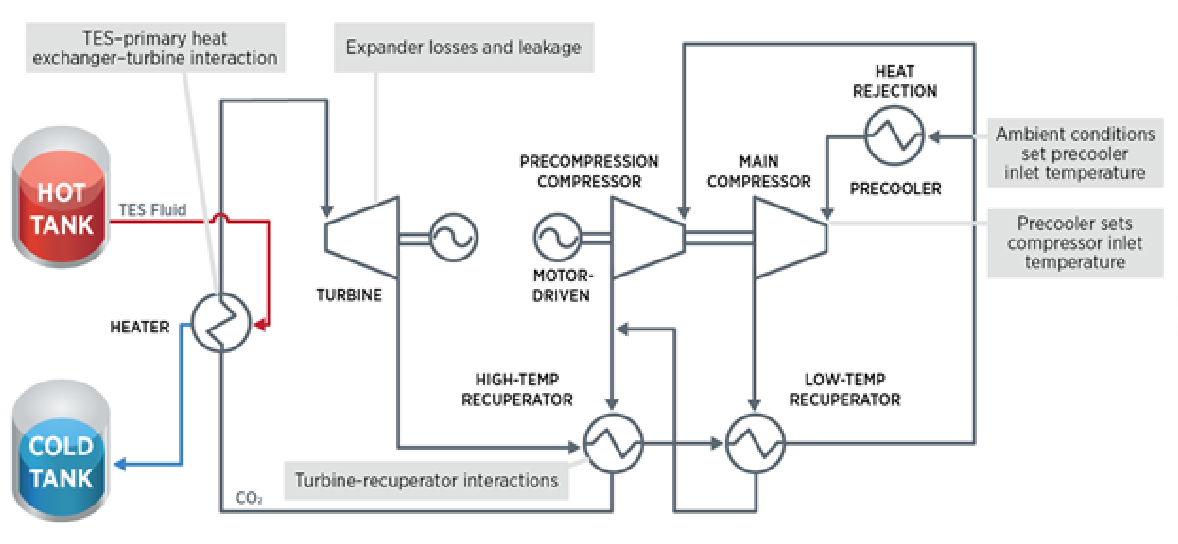


Where to, from Here?



QUESTIONS?

Where to, from Here?



RCBC integrated with thermal energy storage at ~550°C for Integrated TESTBED FOA

Approved Presentation Colors

4 “Bullets” Text Boxes

Text

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Bullet List

Main Bullet

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Agenda Example

Time	Session	Location
8:00AM– 8:30AM	**Introduction** *Charlie Gay, Director, Solar Energy Technologies Office*	Room 100
8:30AM– 10:30AM	**Panel – Title** *Name, Org/Company (Moderator)* *Name, Org/Company* *Name, Org/Company*	Room 100

Success Story – Tall Photo

BACKGROUND

- Bullet 1
- Bullet 2

SUCCESS

- Bullet 1
- Bullet 2

Success Story – Wide Photo

BACKGROUND

- Bullet 1
- Bullet 2

SUCCESS

- Bullet 1
- Bullet 2

Apollo Compressor

APOLLO COMPANDER