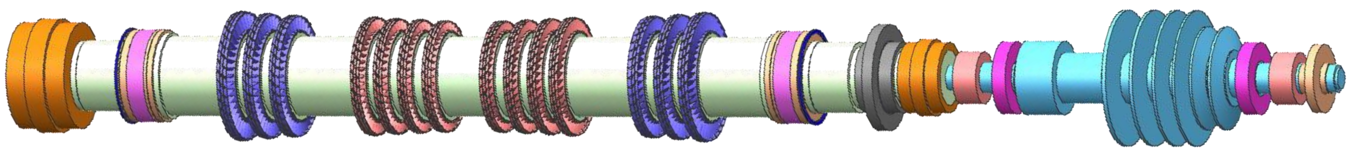
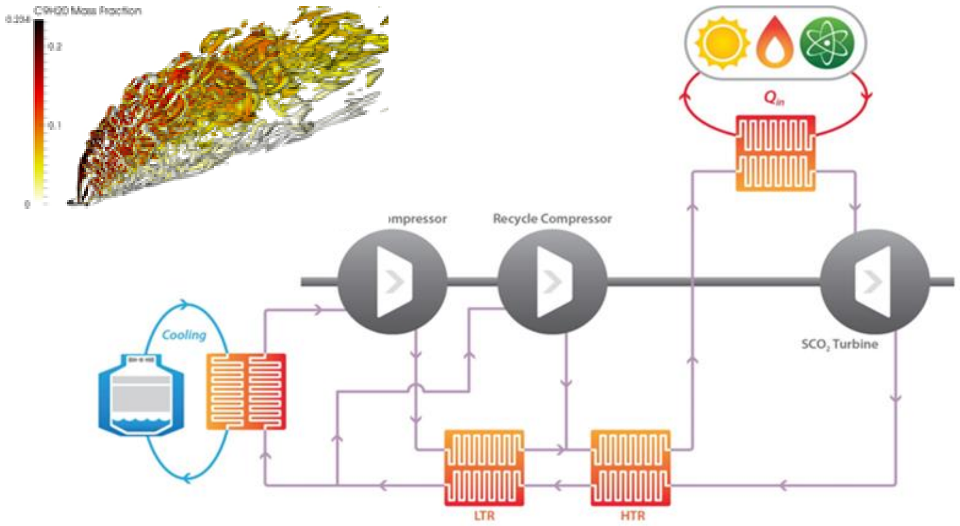
Overview of Supercritical Carbon Dioxide Based Power Cycles for Stationary Power Generation

Presented to: International Seminar on Organic Rankine Cycle Power Systems; Politecnico di Milano; Milano Italy

September 13, 2017





Solutions for Today | Options for Tomorrow

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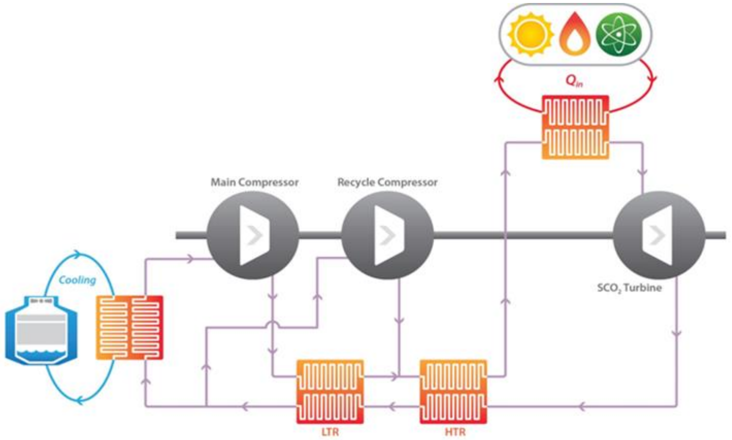
Advanced Turbines and Supercritical
CO_2 Power Cycles Programs
US DOE Office of Fossil Energy
NETL

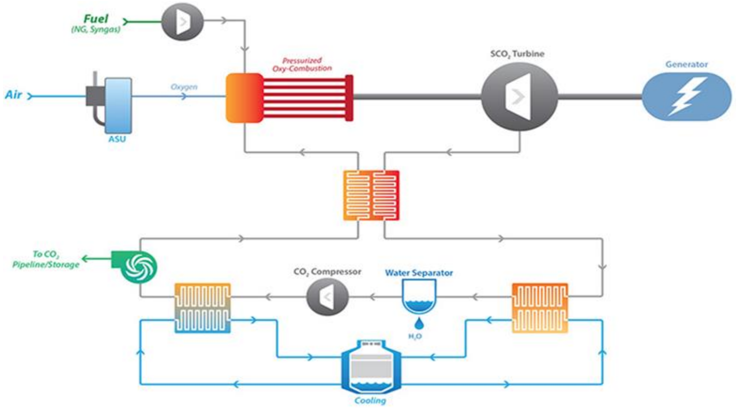
Presentation Outline

Overview of Supercritical Carbon Dioxide Based Power Cycles for Stationary Power Generation

- Introduction to NETL
- DOE's Program on sCO_2 Based Power Cycles
- Overview of sCO_2 Cycles
- FE System Studies with sCO_2 Power Cycles
- Technology Challenges
- Key Projects
- Summary and Conclusions



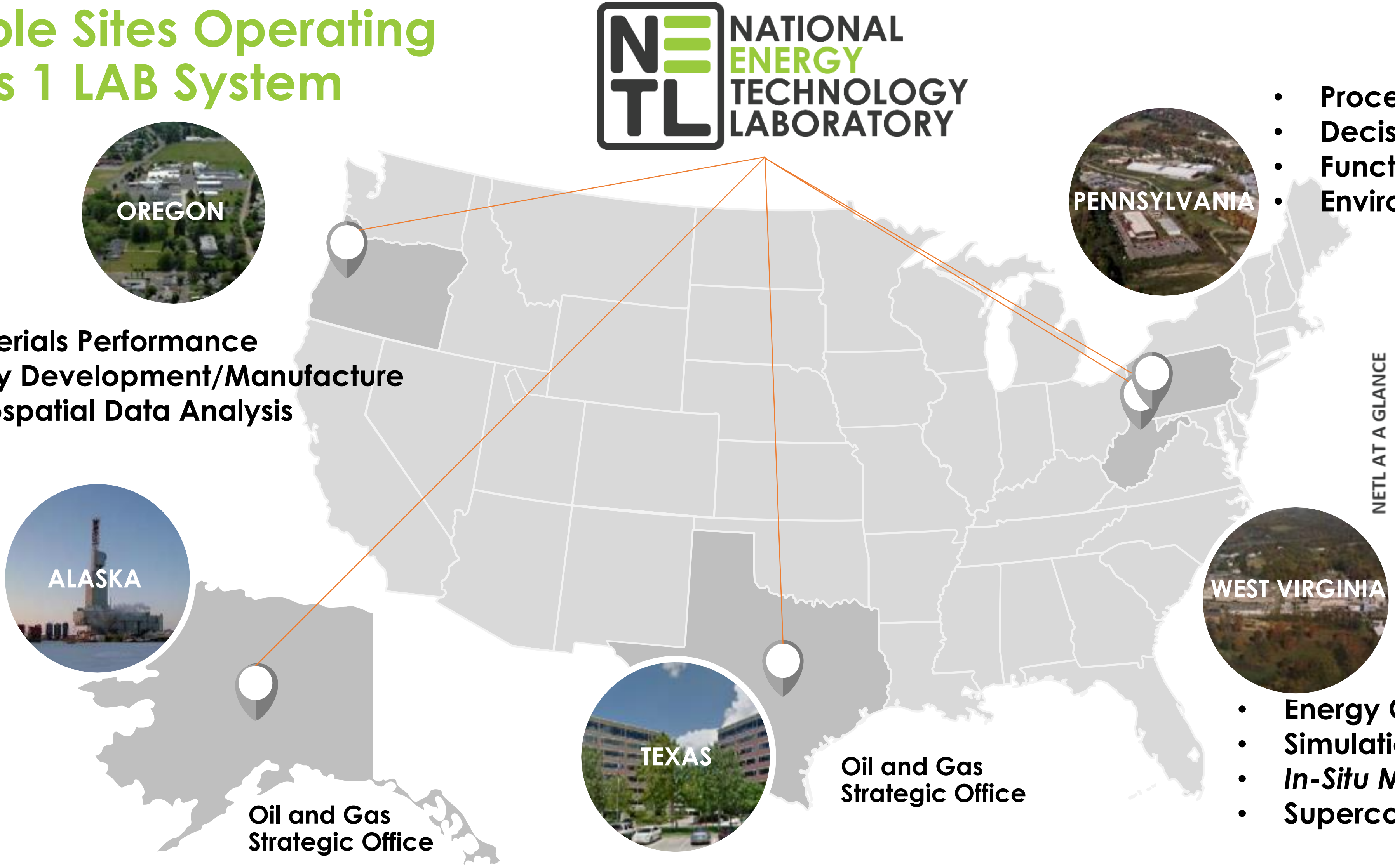
Indirectly-heated cycle



Directly-heated cycle

NETL Structure

Multiple Sites Operating as 1 LAB System



- Materials Performance
- Alloy Development/Manufacture
- Geospatial Data Analysis

Oil and Gas
Strategic Office

Oil and Gas
Strategic Office

- Process Systems Engineering
- Decision Science
- Functional Materials
- Environmental Sciences

NETL AT A GLANCE

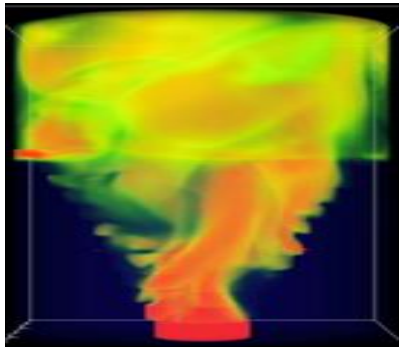
Employee numbers

FTE	FY14	FY15	FY16
SES	6	7	7
EJ	2	2	3
GS	559	542	512
CON	786	776	752
Total	1353	1327	1274

- Energy Conversion Devices
- Simulation-Based Engineering
- *In-Situ* Materials Characterization
- Supercomputer Infrastructure

NETL Core Competencies & Mission

MISSION - Discover, integrate, and mature technology solutions to enhance the nation's energy foundation and protect the environment for future generations

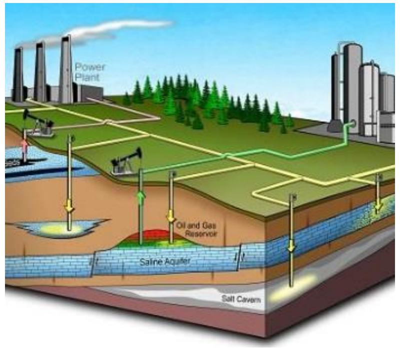


Computational Science & Engineering

- High Performance Computing
- Data Analytics

Materials Engineering & Manufacturing

- Structural & Functional
- Design, Synthesis, & Performance



Geological & Environmental Systems

- Air, Water & Geology
- Understanding & Mitigation

Energy Conversion Engineering

- Component & Device
- Design & Validation

Systems Engineering & Analysis

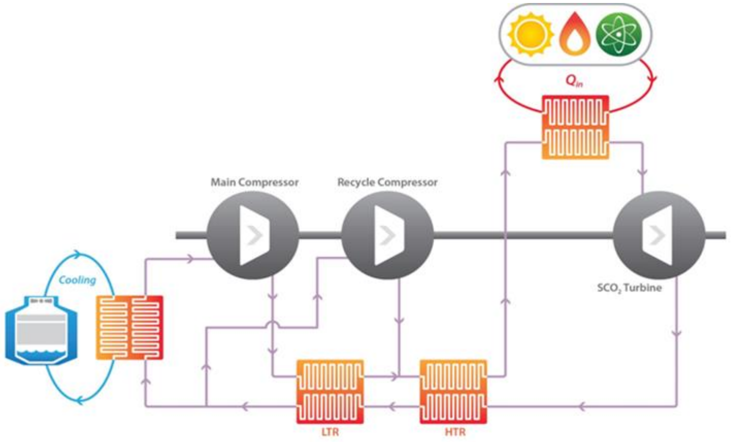
- Process Systems
- Optimization
- Validation & Uncertainty
- Economics
- Energy Market Modeling
- Grid
- Life Cycle Analysis

Program Execution & Integration

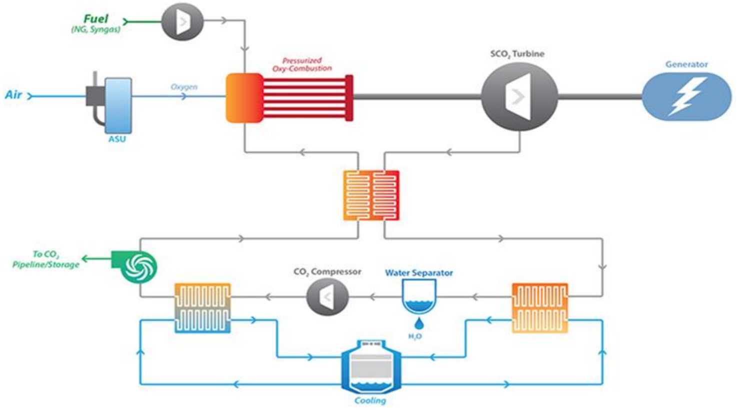
- Technical Project Management
- Market & Regulatory Analysis

Presentation Outline

- Introduction to NETL
- **DOE's Program on sCO_2 Based Power Cycles**
- Overview of sCO_2 Cycles
- FE System Studies with sCO_2 Power Cycles
- Technology Challenges
- Key Projects
- Summary and Conclusions



Indirectly-heated cycle



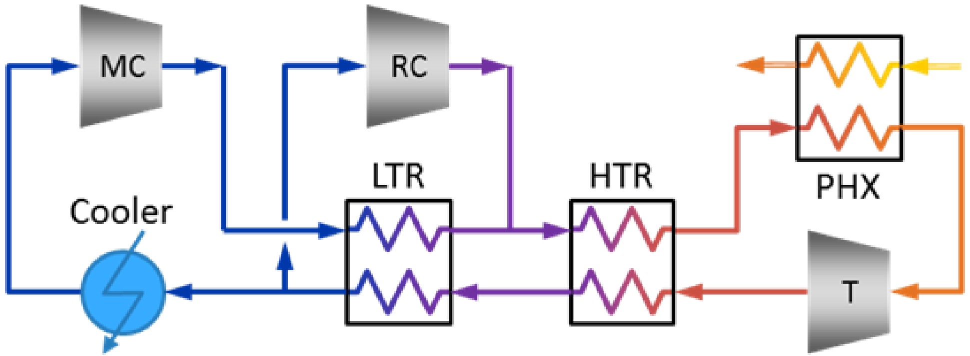
Directly-heated cycle

FE Base Program in sCO_2 Power Cycles

Two related cycles for advanced combustion and gasification applications

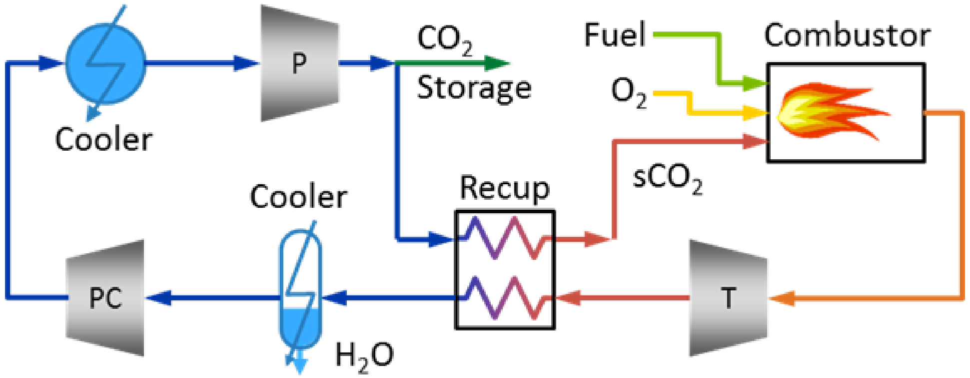
Indirectly-heated cycle (RCB)

- Cycle to be used for 10 MW sCO_2 pilot plant
- Applicable to advanced combustion boilers
- Incumbent to beat: USC/AUSC boilers
- >50% cycle eff. (work out/heat in) possible
- High fluid density, low pressure ratio yields compact turbomachinery
- Ideally suited to constant temp heat sources (NE and CSP)
- Adaptable for dry cooling



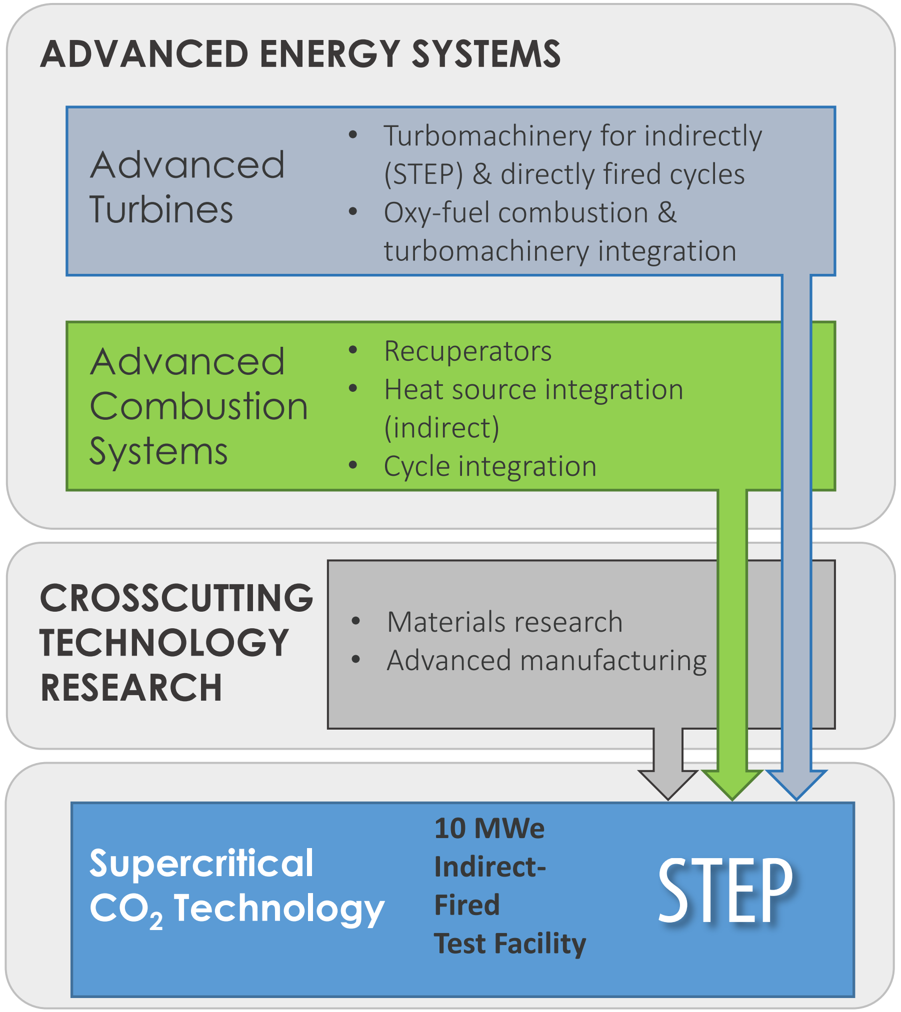
Directly-heated cycle (Allam)

- Fuel flexible: coal syngas and natural gas
- Incumbent to beat: Adv. F- or H-class NGCC w/ post CCS
- Compatible w/ RD&D from indirect cycle
- $>95^+$ % CO_2 capture at storage pressure
- Net water producer, if dry-cooled



FE Programs Supporting sCO_2 Technology

AES (AT & ACS), Crosscutting Technology Research and STEP



ADVANCED ENERGY SYSTEMS

Advanced Turbines
- Turbomachinery for indirectly (STEP) & directly fired cycles
- Oxy-fuel combustion & turbomachinery integration

Advanced Combustion Systems
- Recuperators
- Heat source integration (indirect)
- Cycle integration

CROSSCUTTING TECHNOLOGY RESEARCH
- Materials research
- Advanced manufacturing

Supercritical CO_2 Technology

10 MWe Indirect-Fired Test Facility

STEP

- **FE Base sCO_2 Technology Program**
  - sCO_2 cycle component development funded by individual programs
  - Specific interest in adv. combustion indirect cycle & IGCC direct cycle
  - Near term application to natural gas
- **DOE sCO_2 Crosscut Initiative**
  - Collaboration between DOE Offices (FE, NE, and EERE)
  - Mission: Address technical issues, reduce risks, and mature technology
  - Objective/Goal: Design, build, and test 10 MWe Supercritical Transformational Electric Power (STEP) pilot facility
  - FE designated budget focal for Crosscut Initiative and STEP

DOE sCO_2 Crosscut Initiative

Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency and Renewable Energy (EERE)

- Collaborate on development of sCO_2 power cycles
- Coordinate efforts to solve common challenges to the applications

Mission: Address technical issues, mature technology, reduce risks towards commercialization of the sCO_2 power cycle

Design, build, and operate 10 MWe STEP (Supercritical Transformational Electric Power) indirect-fired sCO_2 power cycle pilot-scale:

- Initial configuration indirect-fired, closed loop recompression Brayton cycle
- Demonstrate component performance, cycle operability, instrumentation and controls, validation of models, and progress toward a lower COE
- Opportunities to resolve technology-specific issues common to multiple potential heat source applications (fossil, nuclear, concentrating solar, geothermal sources, waste heat)

Base R&D portfolios within the three offices continue to address application specific development needs.

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- **Overview of sCO_2 Cycles**
- FE System Studies with sCO_2 Power Cycles
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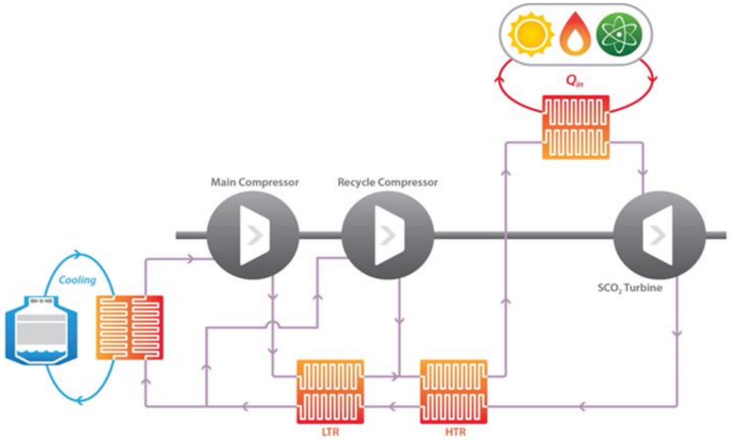
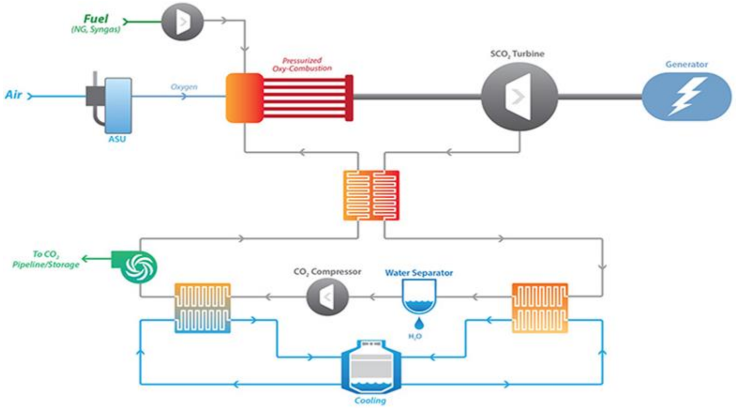


Indirectly-heated cycle



Directly-heated cycle

Why supercritical CO_2 (sCO_2)?

sCO_2 is an ideal fluid for the applications of interest – replacing steam

- **Moderate conditions for supercritical state**
  - CO_2 Critical Point
    - Temperature: 31.06 C , (87.9 ºF)
    - Pressure: 7.4 MPa , (1071.8 psia)
  - Approximately 50% increase in specific heat (Cp) around critical point at likely cycle conditions
- **Excellent fluid properties**
  - Liquid-like densities around the cycle
    - Relatively low critical point temperature
  - Increased density and heat capacity, and reduced compressibility factor near critical point
  - Non-Toxic

Supercritical CO_2 Power Cycle Conditions

FE conditions for the recompression Brayton Cycle (indirect) and Allam Cycle (direct)

Cycle/Component		Inlet		Outlet	
		T (°C)	P (MPa)	T (°C)	P (MPa)
Indirect	Heater	450-535	1-10	650-750	1-10
	Turbine	650-750	20-30	550-650	8-10
	HX	550-650	8-10	100-200	8-10
Direct	Combustor	750	20-30	1150	20-30
	Turbine	1150	20-30	800	3-8
	HX	800	3-8	100	3-8

Working Fluid in the Cycle

Essentially pure CO_2

CO_2 with combustion products including O_2, H_2O, SO_2, HCl

Example

95% CO_2

4% H_2O

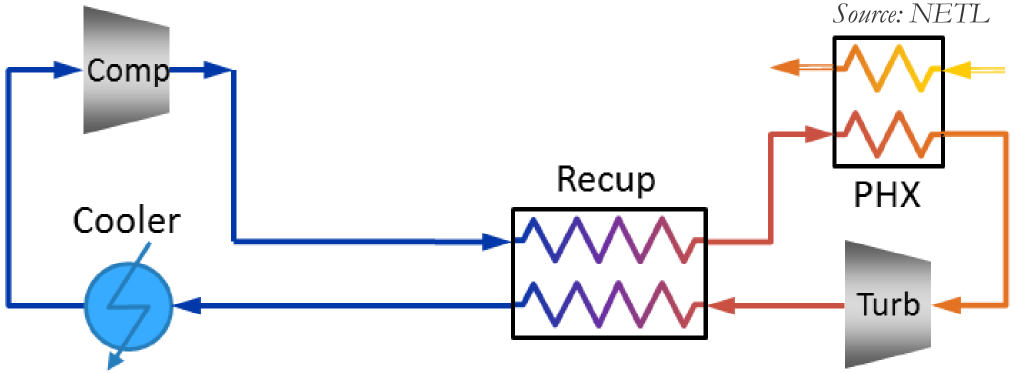
1% O_2

SO_2

HCl

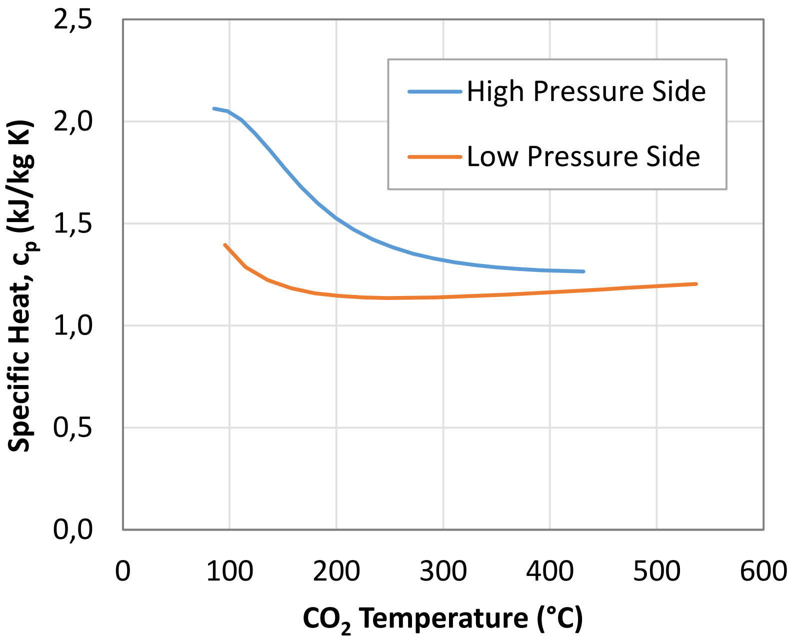
Indirect sCO_2 Power Cycles

The Simple Recuperated sCO_2 Brayton Cycle



Source: NETL

- Most sCO_2 power cycles are derivatives of the simple recuperated Brayton cycle
- Compressor inlet is operated near the critical point for high cycle performance
- Differences in high and low pressure specific heat leads to a large temperature difference at the recuperator's hot end
  - Inefficient recuperation



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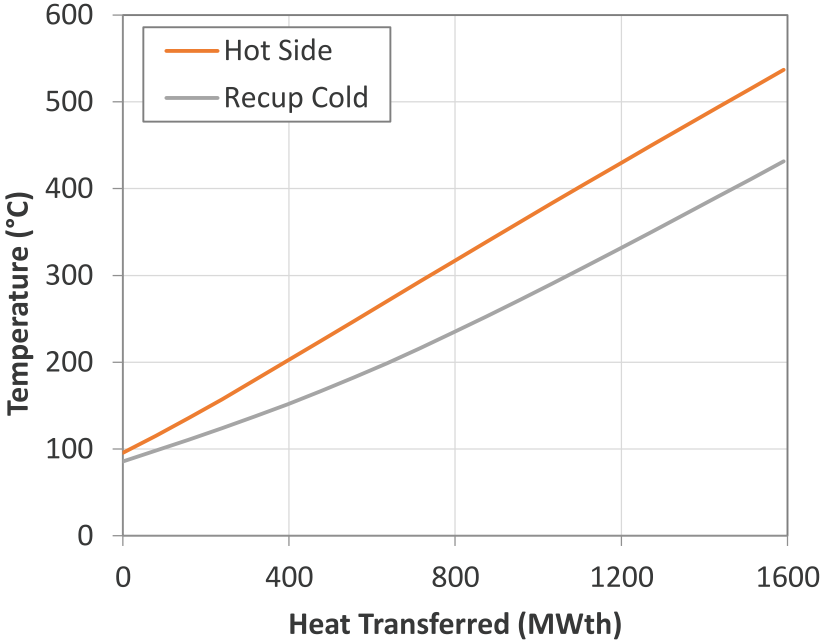


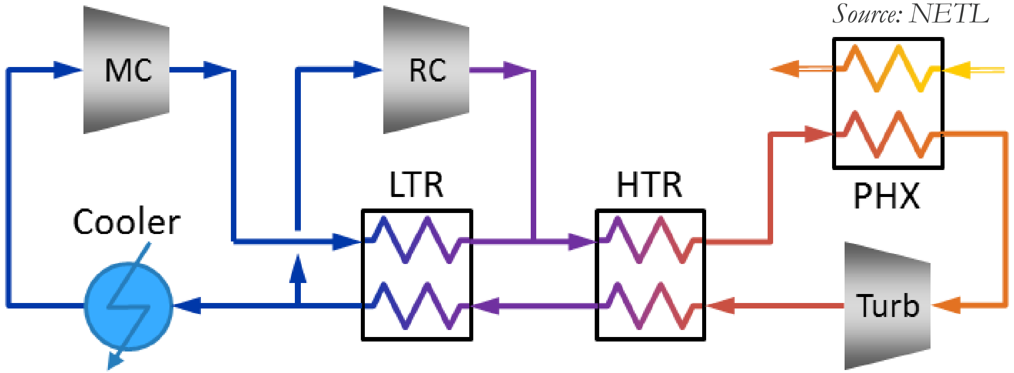
Source: NETL

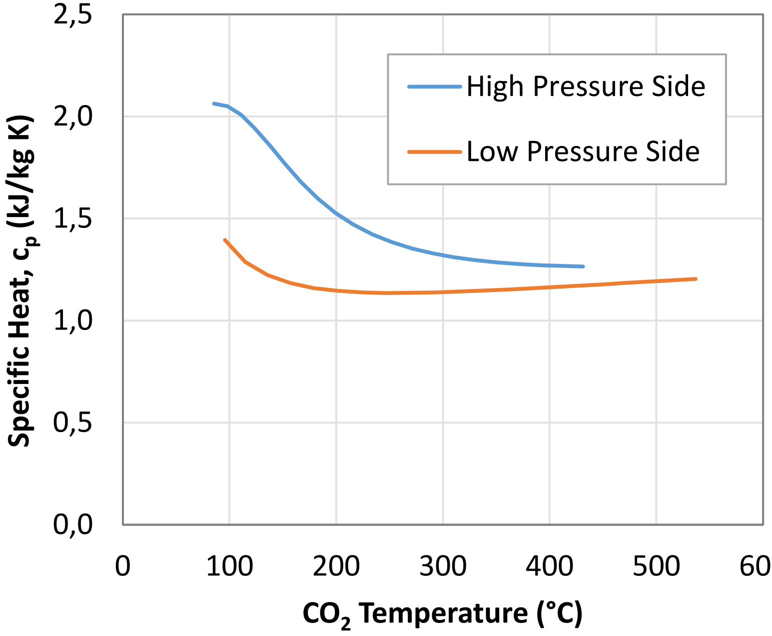
Indirect sCO$_2$ Power Cycles

The Recompression sCO$_2$ Brayton Cycle

- An efficient solution is to split the recuperator into high (HTR) and low temperature recuperators (LTR), and to bypass a portion of the flow around the LTR through a recycle compressor
- The recycle flow is set to achieve a desired approach temperature between the LTR and HTR, at the recycle compressor exit temp.
- This yields more efficient recuperation and a higher overall cycle efficiency

Source: NETL





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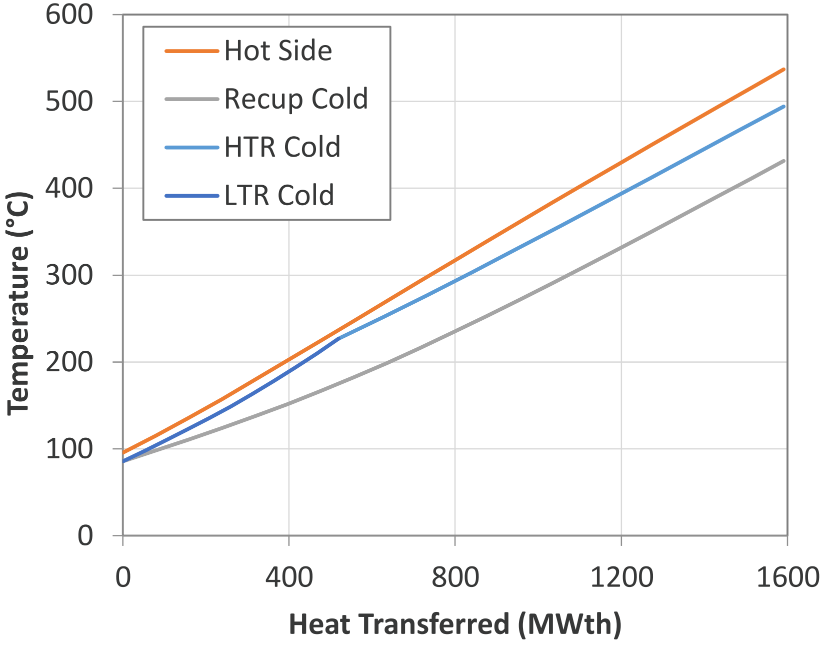
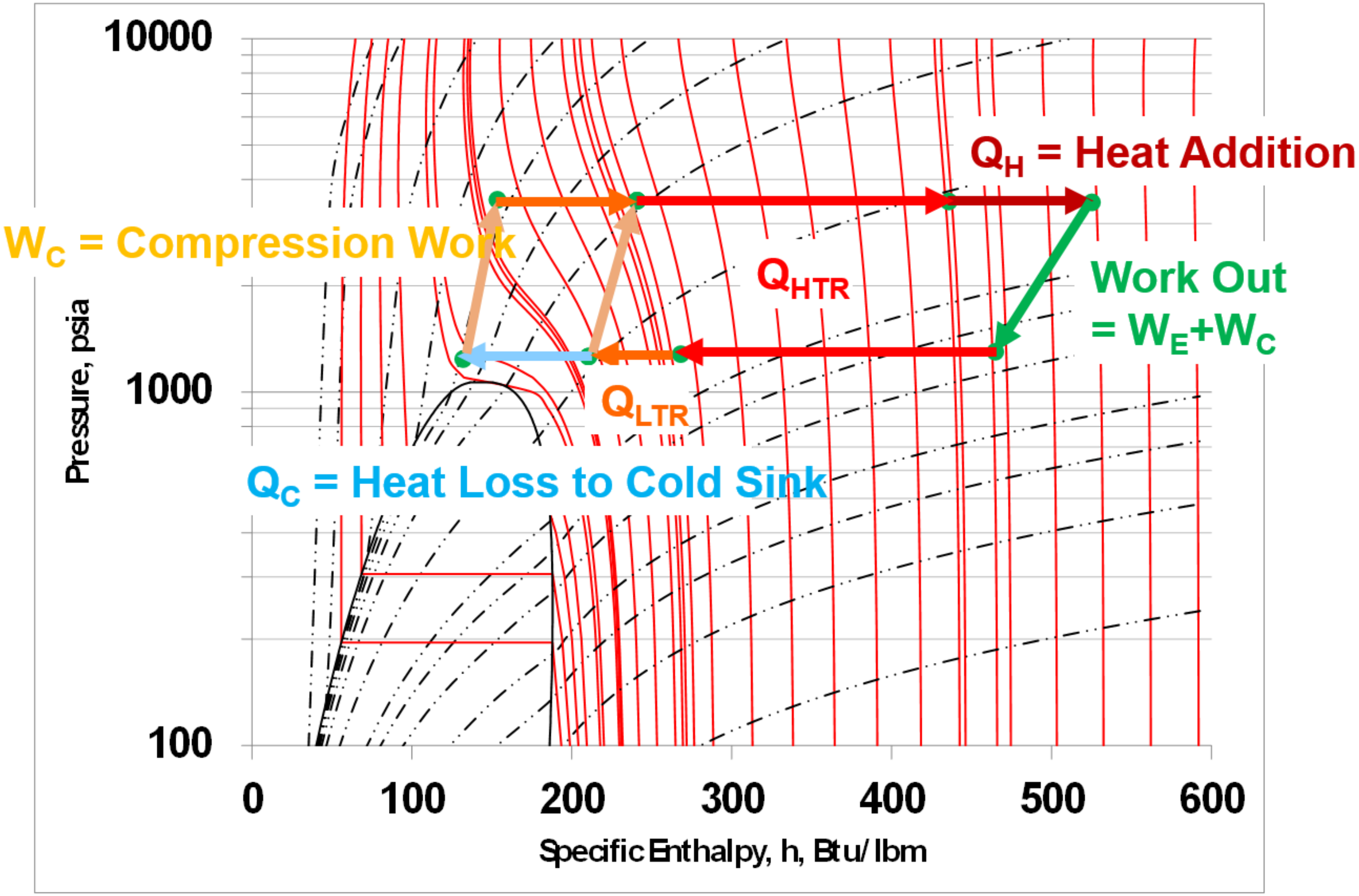


Source: NETL

Recompression Closed Brayton Cycle

~ 2/3 of the heat in the cycle is recuperated

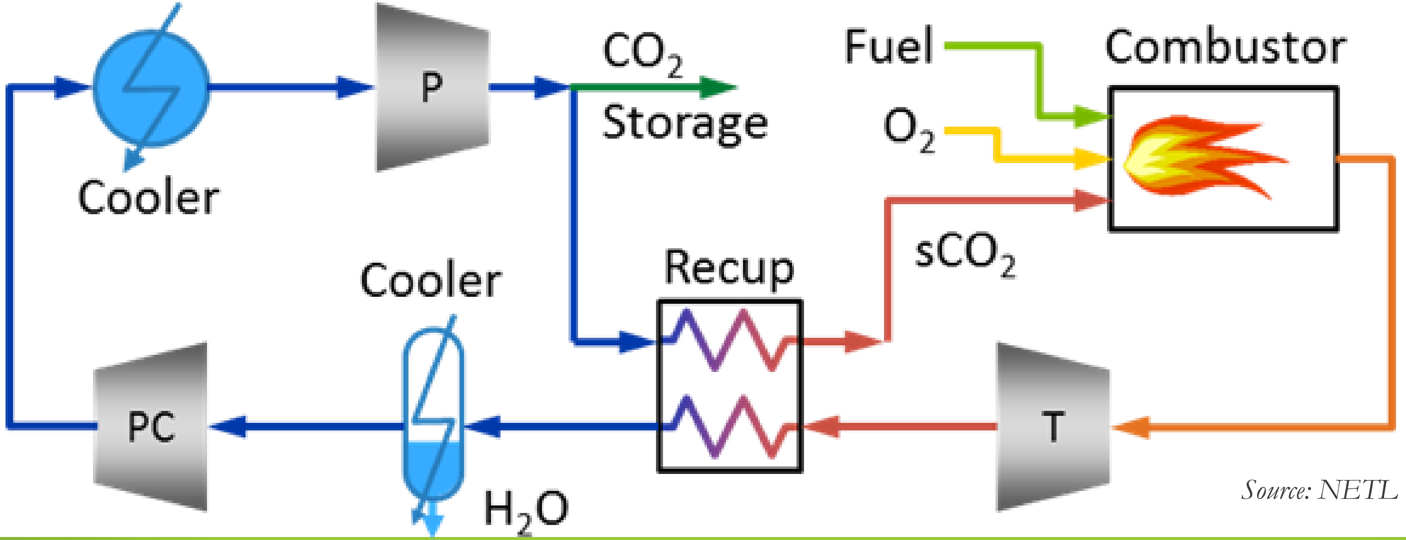


Pressure vs. Specific Enthalpy Diagram

Technology Overview – Allam Cycle

Characteristics and Benefits

- **Direct combustion of gaseous fuels with O2 in sCO_2 working fluid**
  - sCO_2 and water expanded
- **Moderate pressure ratio (8-10), relatively high turbine inlet temperatures ($T_{in} \leq$ 1200 °C)**
  - Cycle limited by recuperator inlet temperature
- **Recuperation of heat to sCO_2 recycled to the combustor significantly improves efficiency**
- **High purity CO_2 ready for storage or EOR**
- **Low or no water consumption**
  - Water producing cycle if dry cooling is used



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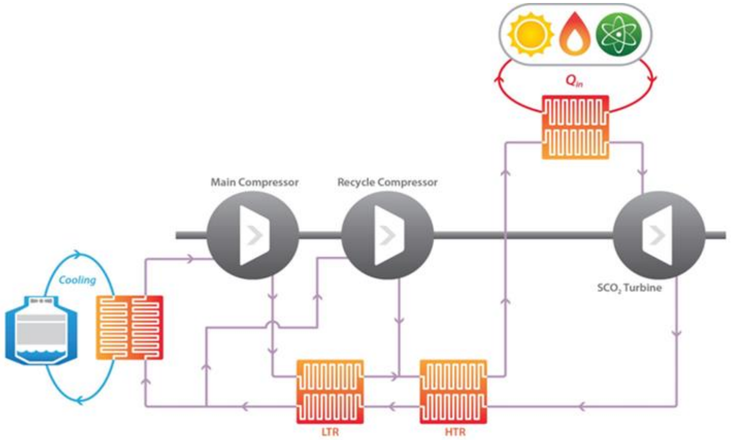
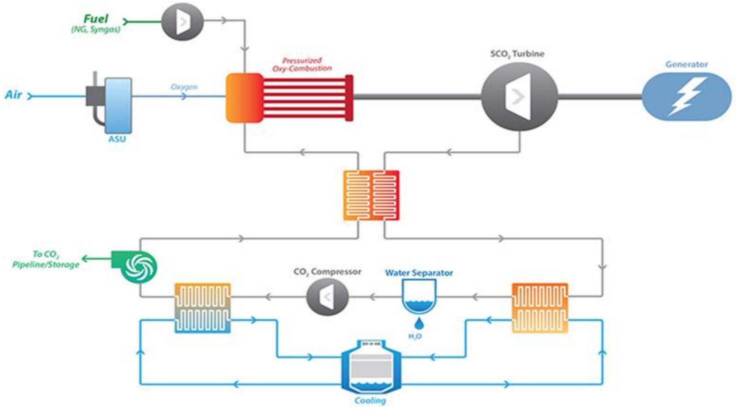


Indirectly-heated cycle

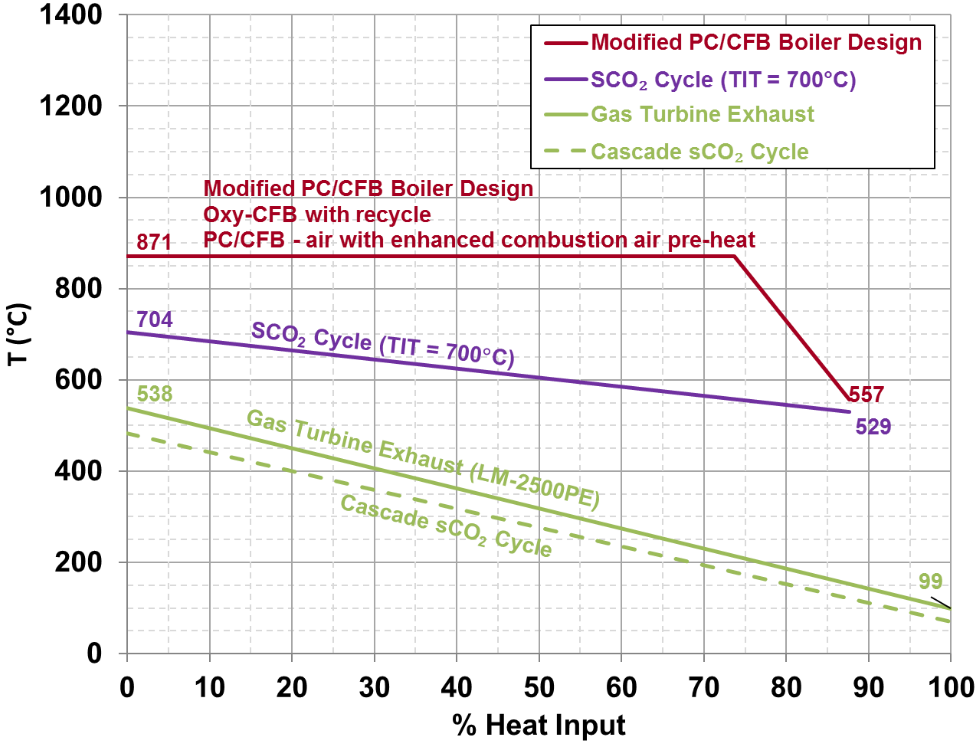


Directly-heated cycle

Utility-Scale Indirect sCO_2 Plant Study

Overview

- <u>Objective</u>: Establish cost and performance baselines for commercial-scale indirect sCO_2 power plants with CCS
- Early work shows that the narrow temperature addition window of a recompression sCO_2 Brayton Cycle restricts boiler selection
  - Modified Oxy-CFB boilers with CCS chosen for analysis
  - Recompression cycle with reheat and/or main compressor intercooling (4 combinations x 2 temperatures)
- Performance Comparisons
- Economic Comparisons & Sensitivities
- Potential for Improved Efficiency – Alternate Cycles

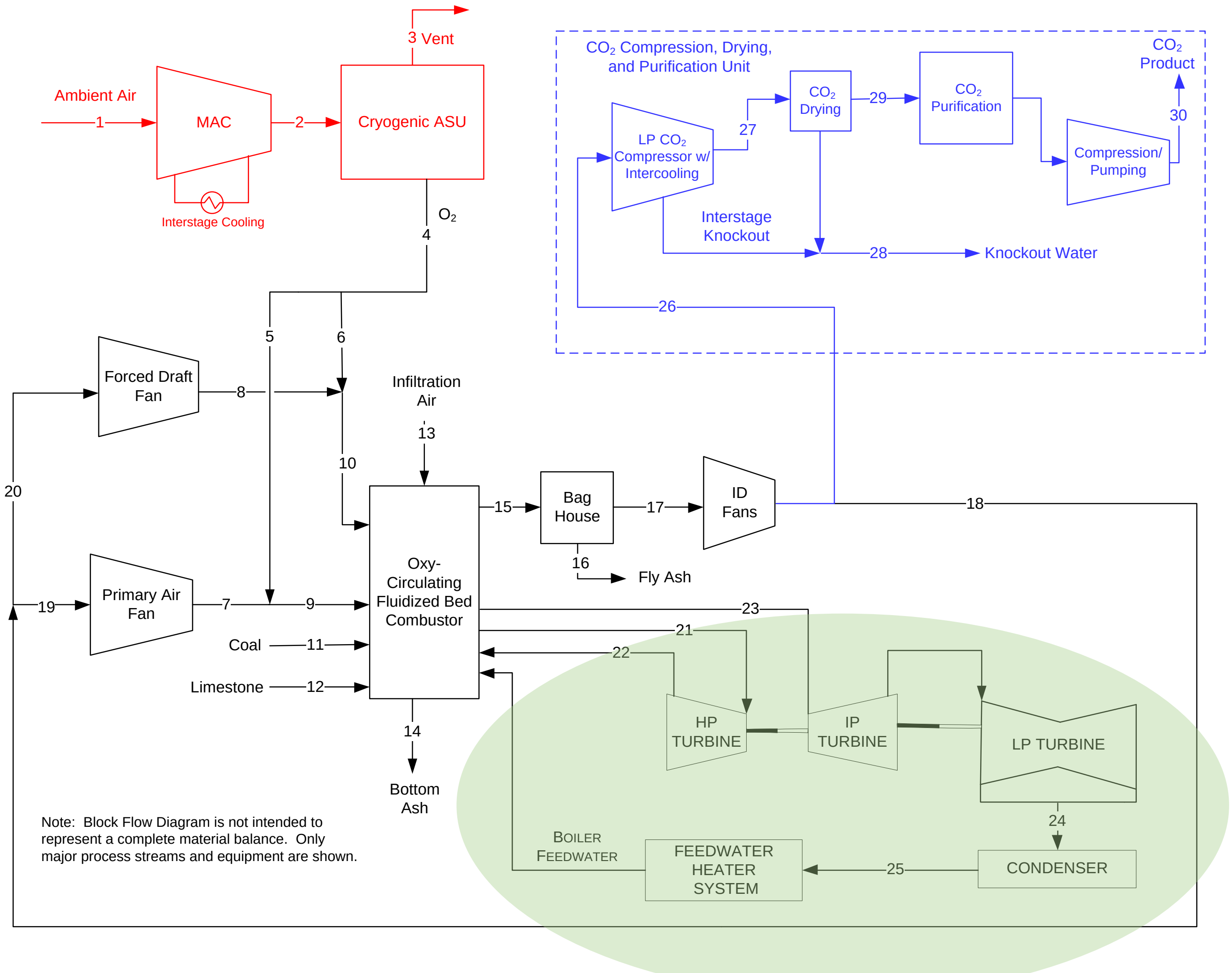


Source: NETL

Oxy-CFB Coal-fired Rankine Cycle Power Plant

Steam Rankine Comparison Cases

- **LP Cryogenic ASU**
  - 99.5% O_2
  - 3.1% excess O_2 to CFB
- **Atmospheric oxy-CFB**
  - Bituminous coal
  - 99% carbon conversion
  - In-bed sulfur capture (94%), 140% excess $CaCO_3$
  - Infiltration air 2% of air to ASU MAC
- **Operating conditions for Rankine plants**
  - Supercritical (SC) Rankine cycle
    (Case B22F: 24.2 MPa/ 600 °C/ 600 °C)
  - Advanced ultra-supercritical (AUSC) Rankine cycle
    (Case B24F: 24.2 MPa/ 760 °C / 760 °C)
- **No low temperature flue gas heat recovery**
- **45% flue gas recycle to CFB**
- **CO_2 purification unit**
  - ~100% CO_2 purity
  - 96% carbon recovery



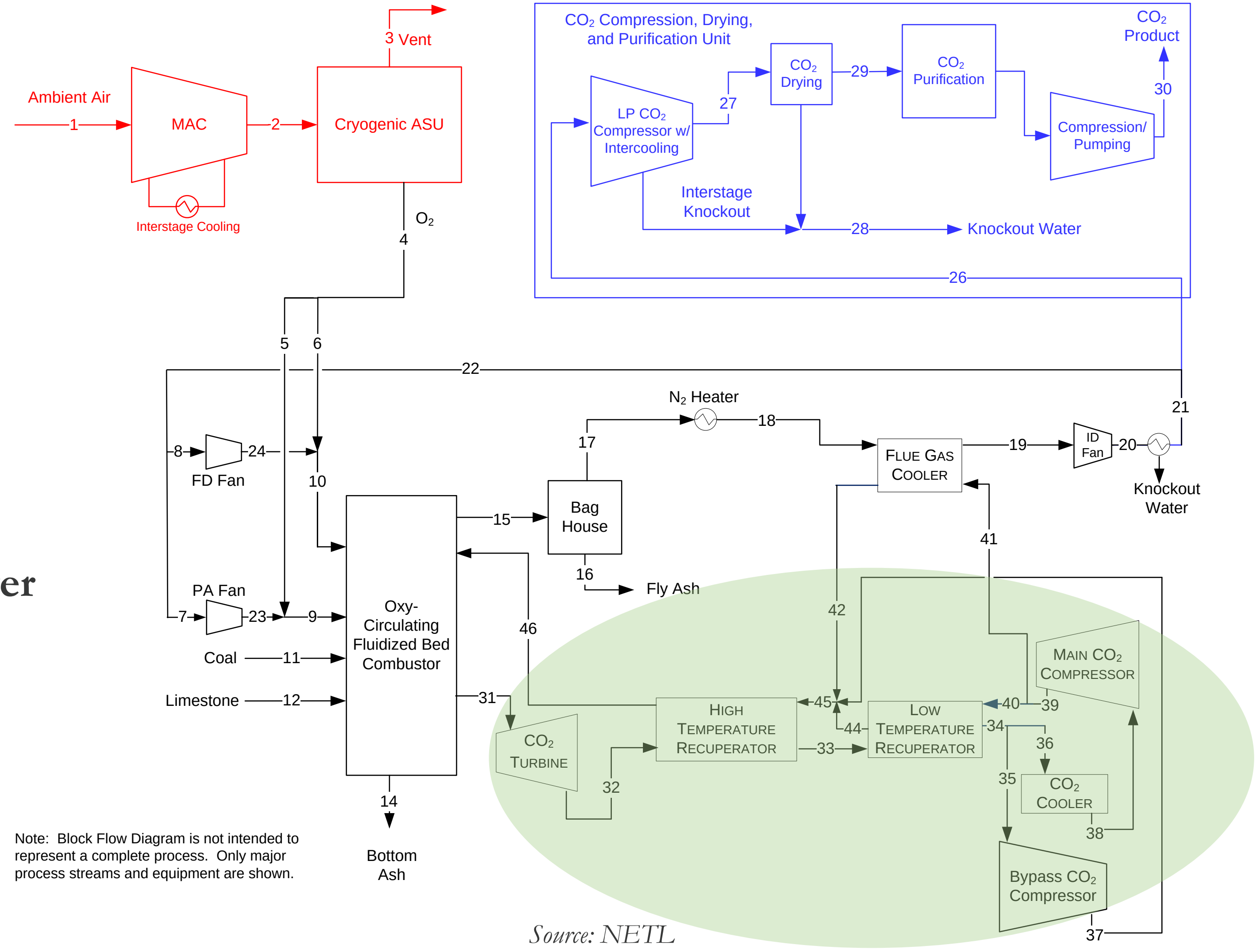
Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Source: NETL

Oxy-CFB Coal-fired Indirect sCO_2 Power Plant

Baseline sCO_2 process

- **LP Cryogenic ASU**
  - 99.5% O_2
  - 3.1% excess O_2 to CFB
- **Atmospheric oxy-CFB**
  - Bituminous coal
  - 99% carbon conversion
  - In-bed sulfur capture (94%), 140% excess $CaCO_3$
  - Infiltration air 2% of air to ASU MAC
- **Recompression sCO_2 Brayton cycle**
  - Turbine inlet temperature 620 °C and
  - Turbine inlet temperature 760 °C
- **Low temperature flue gas heat recovery in sCO_2 power cycle**
- **45% flue gas recycle to CFB**
- **CO_2 purification unit**
  - ~100% CO_2 purity
  - 96% carbon recovery



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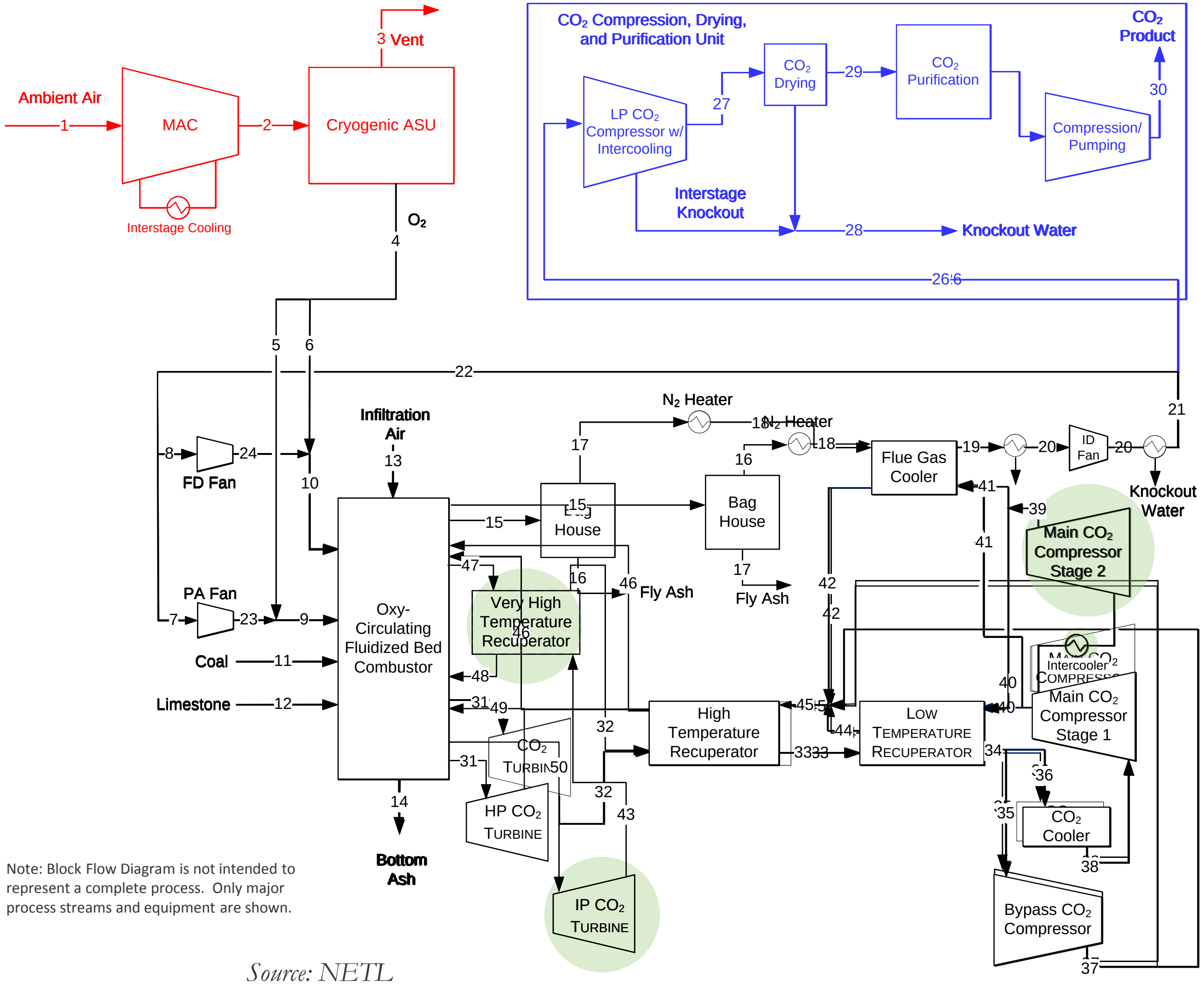
Source: NETL

Oxy-CFB Coal-fired Indirect sCO_2 Power Plant

sCO_2 cycle configurations analyzed

- **Baseline configuration**
- **Reheat sCO_2 turbine**
- **Intercooled 2-stage main sCO_2 compressor**
- **Reheat sCO_2 turbine and Intercooled main sCO_2 compressor**

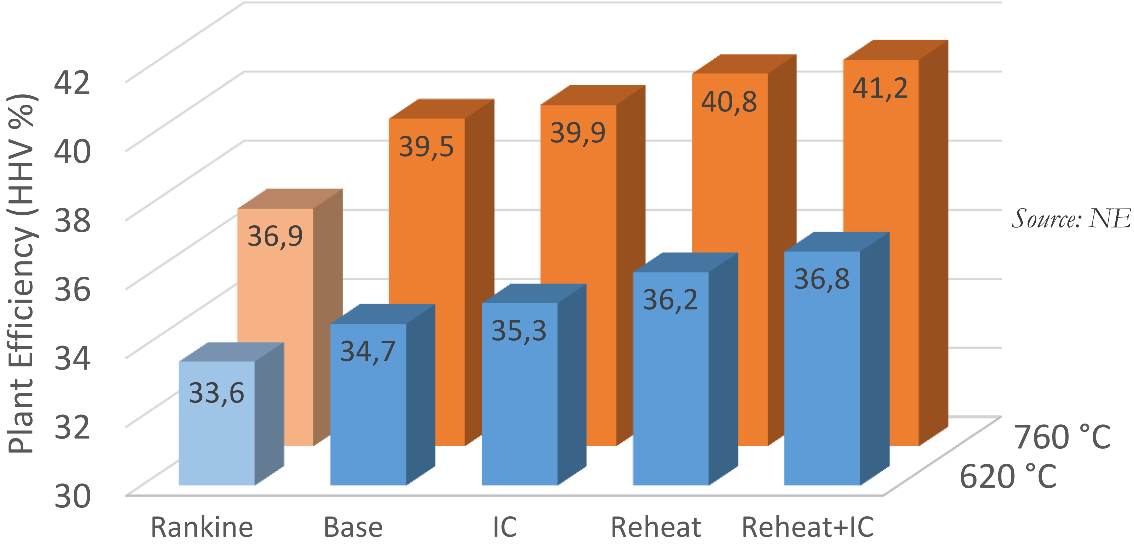


Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

Source: NETL

Summary of Overall Plant HHV Efficiencies

- **Relative to the steam Rankine cycles:**
  - At 620 °C, sCO_2 cycles are 1.1 – 3.2 percentage points higher in efficiency
  - At 760 °C, sCO_2 cycles are 2.6 – 4.3 percentage points higher
- **The addition of reheat improves sCO_2 cycle efficiency by 1.3 – 1.5 percentage points**
- **The addition of main compressor intercooling improves efficiency by 0.4 – 0.6 percentage points**
  - Main compressor intercooling reduces compressor power requirements for *both* the main and bypass compressors



Source: NETL

Power Summary (MW)	B22F	Base	IC	Reheat	Reheat+IC
Coal Thermal Input	1,635	1,586	1,557	1,519	1,494
sCO_2 Turbine Power	721	1,006	933	980	913
CO_2 Main Compressor		160	154	148	142
CO_2 Bypass Compressor		124	60	117	58
Net sCO_2 Cycle Power	721	711	708	704	702
Air Separation Unit	85	83	81	79	78
Carbon Purification Unit	60	56	55	54	53
Total Auxiliaries, MWe	171	161	158	154	152
Net Power, MWe	550	550	550	550	550

Overview - Costing Methodology

sCO_2 Cycle Components

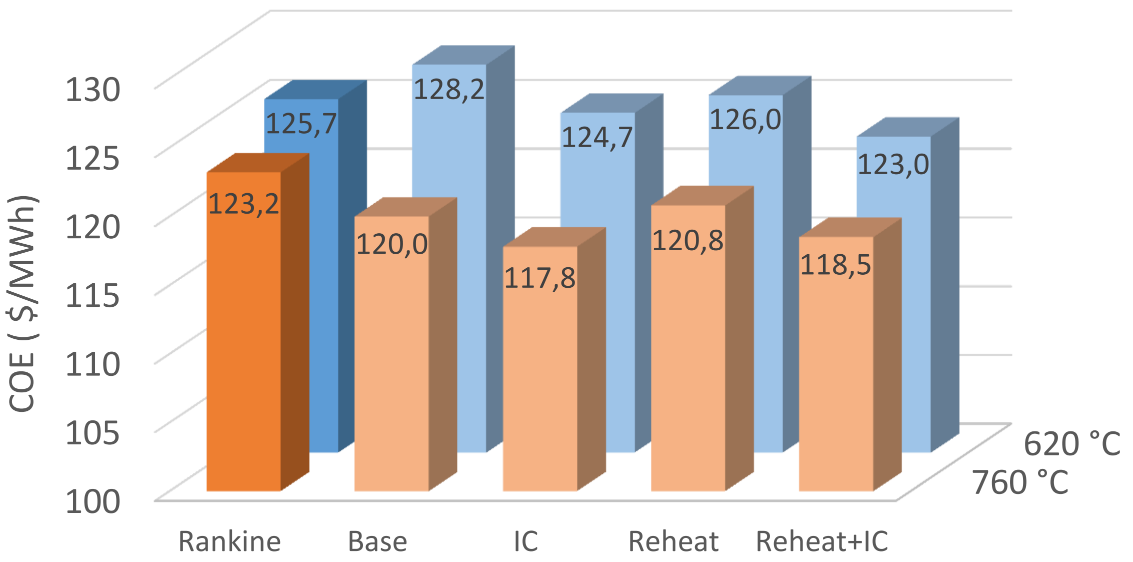
- **sCO_2 Compressors (Main and Bypass):**
  - Based on vendor quotes and scaled using power requirement, inlet volumetric flowrate, and inlet temperature. 60% installation factor added.
- **sCO_2 Heat Exchangers (LTR, HTR and sCO_2 Cooler):**
  - Cost basis taken from 2014 Aerojet Rocketdyne report on recuperators for commercial-scale sCO_2 plants.
  - Sensitivity performed on higher recuperator costs
- **sCO_2 Turbine:**
  - Cost for Baseline 760 °C case taken from literature. Other cases scaled based on output power, turbine inlet temperature, and volumetric flow rate plus vendor information.
- **sCO_2 Piping Cost:**
  - Based on lowest cost material suitable for given service (T, P). Based on data from NETL Report "Report on newly developed A-USC Materials"
- **CFB Boiler Costs:**
  - Cost basis from reference SC Rankine case (B22F) and scaled based on heat duty (80%) and driving force (20%). 90% installation factor.
  - Not adjusted for higher sCO_2 mass flow rate or advanced materials required for 760 °C use.

Summary of COE

Steam Rankine vs. sCO_2 Cases

- **Note that there is significant uncertainty in the CFB and sCO_2 component capital costs (-15% to +50%)**
- **Large capital cost uncertainties being addressed in projects funded by NETL, EPRI and OEM(s):**
    - sCO_2 turbine (GE, Doosan, Siemens)
    - Recuperators (Thar Energy, Brayton Energy, Altex)
    - Primary heat exchanger (B&W, GE)
- **sCO_2 cases have comparable COE to steam Rankine plant at 620 °C, and lower COE for 760 °C cases**

w/o transportation and storage (T&S) costs



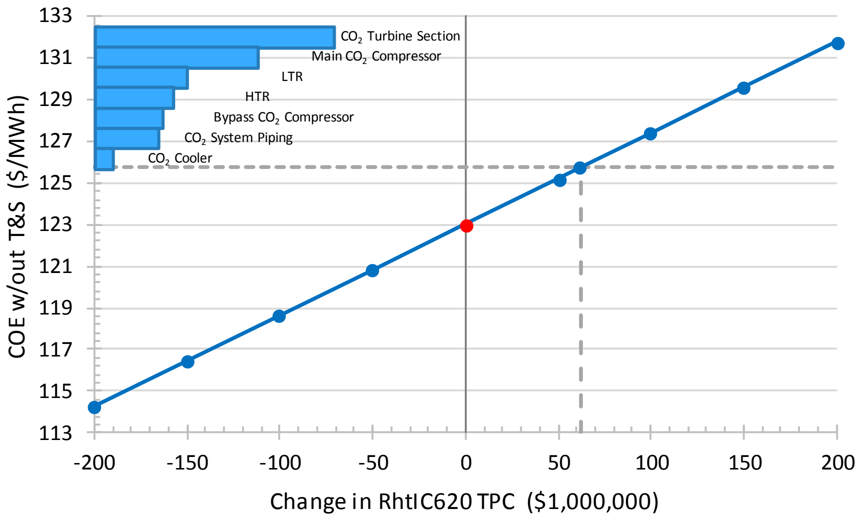
Source: NETL

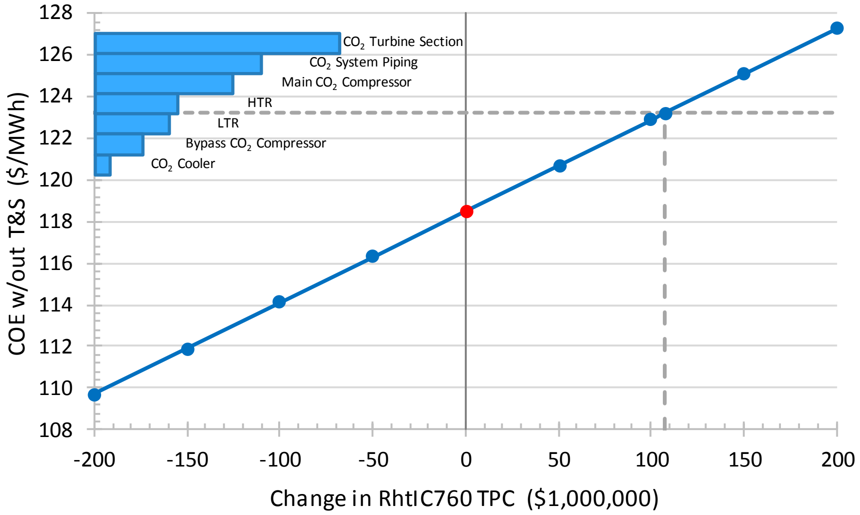
- **Main compressor intercooling improves COE 2.2 – 3.5 $/MWh**
    - Low cost means of reducing sCO_2 cycle mass flow
- **Reheat reduces the COE for the 620 °C cases, but increases COE for turbine inlet temperatures of 760 °C**
    - Due to the high cost of materials for the reheat portions of the cycle in 760 °C cases

Sensitivity Analysis Results Summary

sCO_2 power cycle component TPC, COE versus ΔTPC

- **The COE for both Reheat and Intercooling cases is below the COE for the corresponding Rankine cases**
- **The plot shows how much the sCO_2 plant TPC would have to increase to reach the same COE as the corresponding Rankine plant**
- **At SC conditions, the sCO_2 plant TPC would have to increase \$62MM in order to increase the COE to that for the SC Rankine plant**
- **At AUSC conditions, the sCO_2 plant TPC would have to increase \$108MM in order to increase the COE to that for the AUSC Rankine plant**

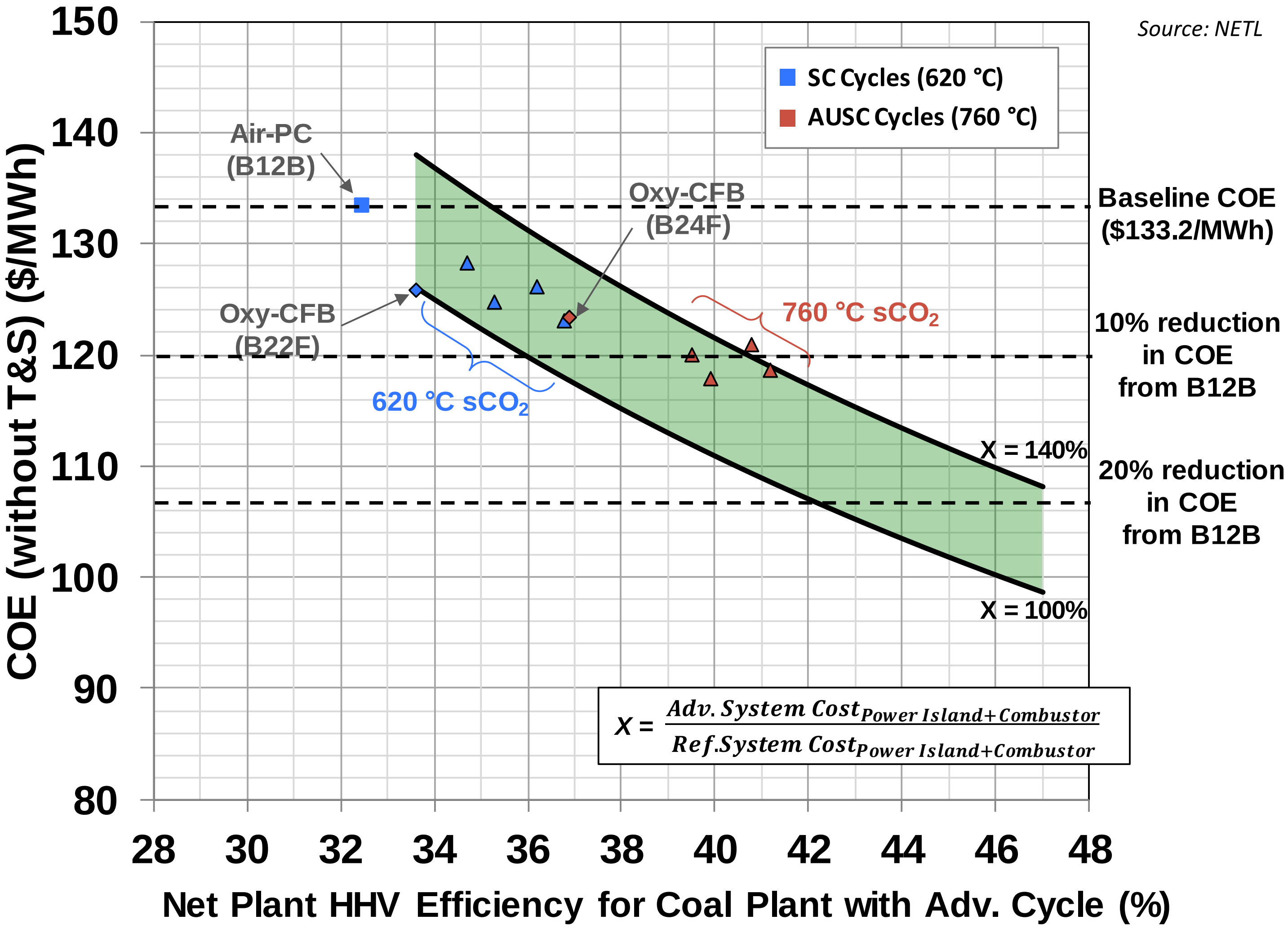




Comparison of sCO_2 versus Rankine Cases

COE vs. Process Efficiency Analysis, with CCS

- **Reference: Supercritical Oxy-combustion CFB with Auto-refrigerated CPU (Case B22F)**
  - \$0/tonne CO_2 Revenue
  - 550 MWe
- **COE reductions are relative to an air fired, supercritical PC coal plant with CCS (B12B)**
- **Higher efficiency and lower COE for sCO_2 cycles relative to steam**
  - Large uncertainty in commercial scale sCO_2 component costs
- **Further improvements to the sCO_2 cycle are currently under investigation**



$$X = \frac{Adv.\,System\,Cost_{Power\,Island+Combustor}}{Ref.System\,Cost_{Power\,Island+Combustor}}$$

Source: NETL

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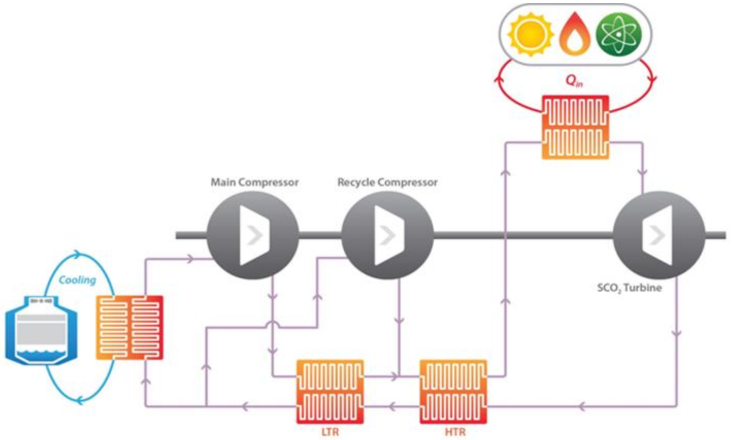
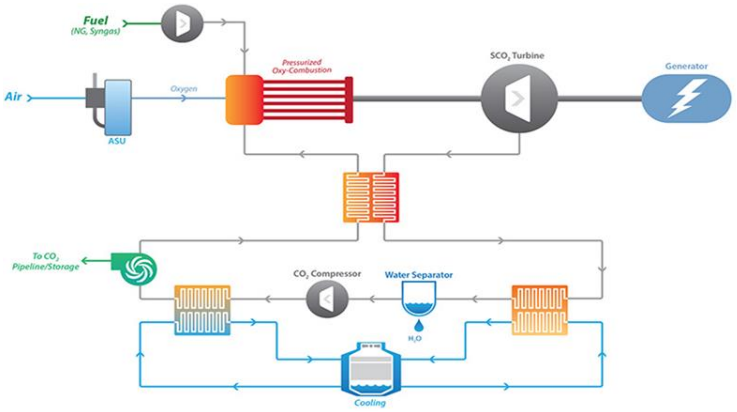
- DOE's Program on sCO_2 Based Power Cycles
- Overview of sCO_2 Cycles
- FE System Studies with sCO_2 Power Cycles
- **Technology Challenges**
- Key Projects
- Summary and Conclusions



Indirectly-heated cycle



Directly-heated cycle

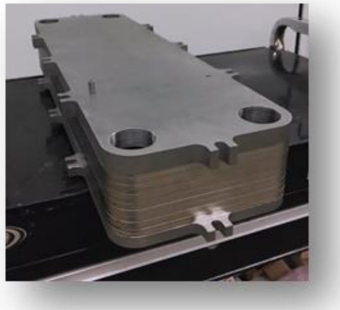
Recuperator R&D

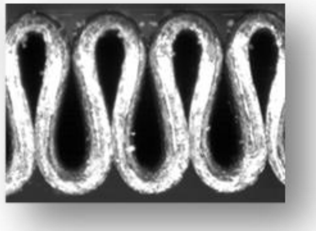
Objectives

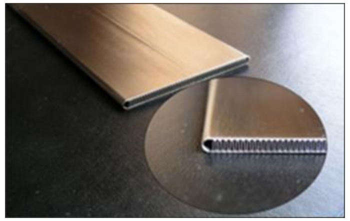
- Maximize heat transfer efficiency
- Minimize pressure drop
- Ensure even flow distribution
- Minimize Cost

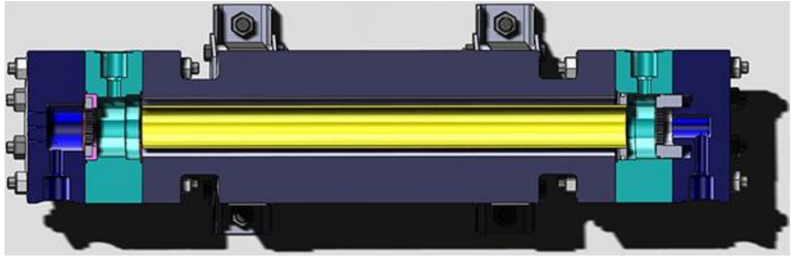
Challenges

- Seals and pressure containment
- Materials strength and stability
- Oxidation resistance
- Fouling effects









Recuperators – Basic Heat Transfer

- Heat transfer coefficient (U) increases with an increase in turbulence, but so does pressure drop
- Increasing heat transfer coefficient allows less contact area (A) and a smaller heat exchanger
- However for a given heat exchanger design, increasing U comes with the penalty of increased pressure drop

$$Q = U \times A \times \Delta T$$

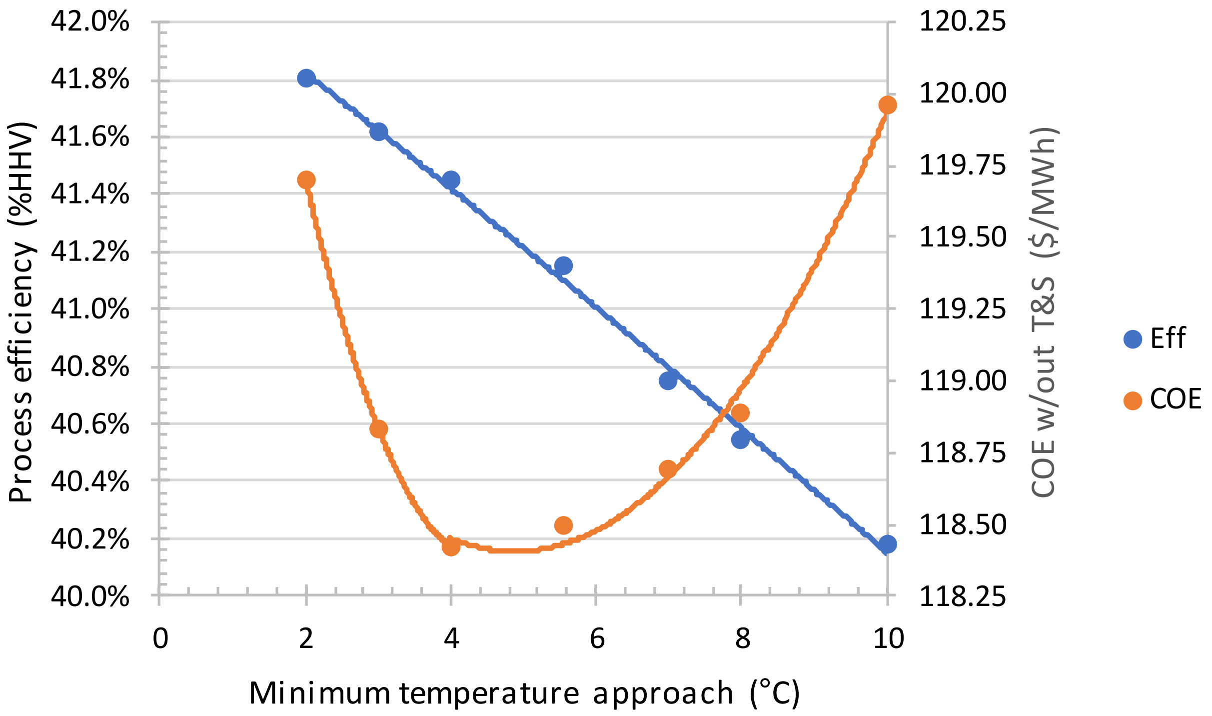
Heat Transfer = Overall HX Coefficient * Area * Temperature Difference

- As ΔT decreases, effectiveness increases, but the area must increase to make up for the decrease in ΔT
- Increasing the contact area generally results in an increase in volume of material required → $$$

Sensitivity Analysis Results Summary

Minimum recuperator temperature approach (**Tapp**) for sCO_2 with reheat & intercooling with 760 °C TIT

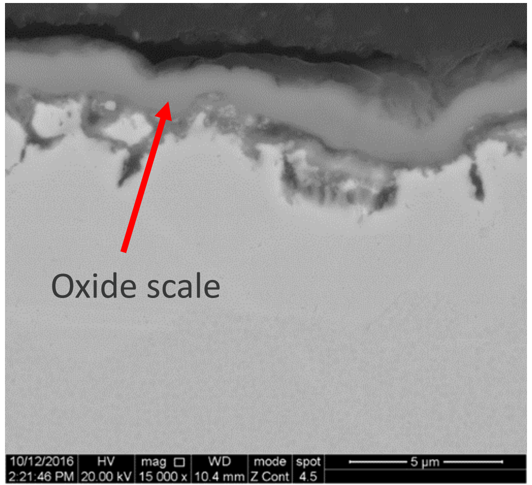
- **Tradeoffs that impact results**
  - Low minimum **Tapp** increases recuperator effectiveness and increases power output from the cycle, increasing efficiency and lowering COE
  - Low minimum Tapp increases recuperator area and cost and increases pressure drop though the recuperator lowering efficiency
- **Key results for minimum Tapp**
  - Higher efficiency as minimum Tapp decreases
  - Minimum COE at minimum Tapp = 4-5 °C
- **Limits**
  - Minimum Tapp lower than 4 °C was not economically attractive



Potential sCO_2 Material Degradation Pathways

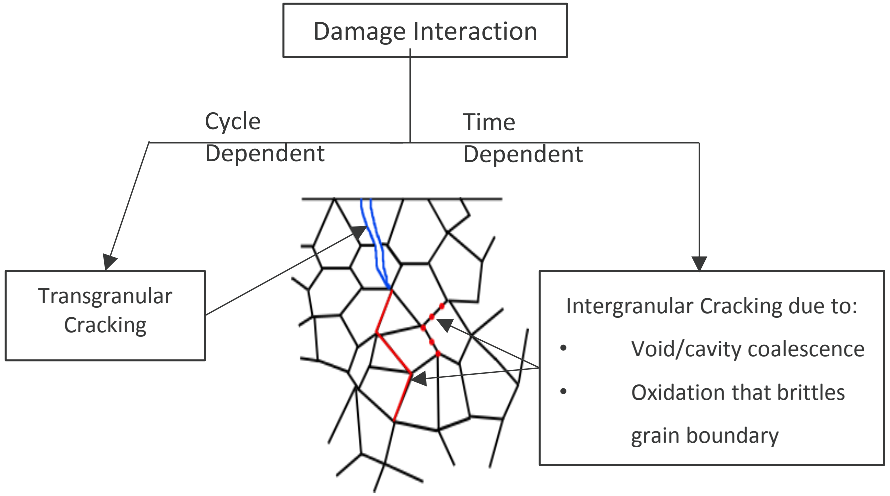
Corrosion

- **Degradation of material surface through chemical reactions**
- **Oxidation**
  - CO_2 dissociates into CO and O_2
  - CO_2 (g) ↔ 0.5 O_2 (g) + CO (g)
  - O_2 reacts and forms oxides on metal surfaces
- **Carburization**
  - Carbon ingress into material resulting in formation of subsurface metal carbides
  - 2 CO (g) ↔ C (s) + CO_2 (g)
- **Goal: form a thin protective external oxide layer to prevent oxidation**
  - Oxidation of Cr or Al in the material to form Cr_2O_3 or Al_2O_3



Creep and Fatigue

- **Creep**: tendency of a solid material to deform slowly and permanently due to mechanical stresses below its yield strength at elevated temperatures.
- **Fatigue**: failure mechanism that occurs when component experiences cyclic stresses or strains that produce permanent damage.
- Expected that oxidation further degrades creep-fatigue life.



Damage Interaction

Cycle Dependent

Time Dependent

Transgranular Cracking

Intergranular Cracking due to:

- Void/cavity coalescence
- Oxidation that brittles grain boundary

Unique Challenges for Materials

sCO_2 Environment

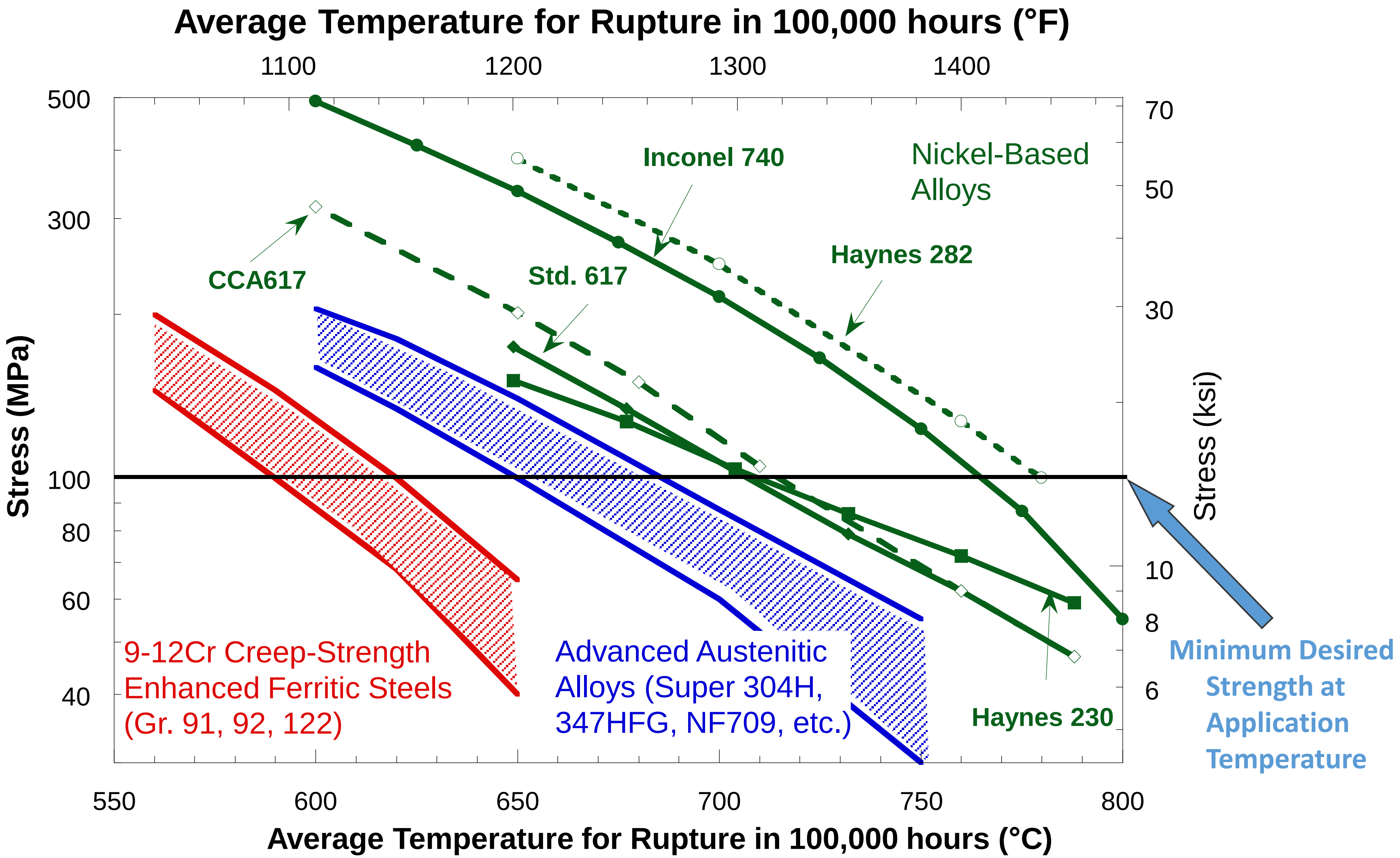
- Can cause chemical instabilities on surface of materials (oxidation potential, carburization potential)
- Oxidation and carburization can take place in growing cracks on components under cyclic loading
  - Cause mechanical instabilities which can lead to premature failure
- Creep life of thin wall sections in compact heat exchangers may be lower than bulk properties of that material
- High velocity turbulent flow of dense sCO_2 can cause erosion
- Materials joined by welding, diffusion bonding, or brazing may be affected by the sCO_2 environment
- Greater challenges posed by direct sCO_2 cycles due to more corrosive chemistry of the working fluid (CO_2, O_2, H_2O, and impurities) and higher operating temperature

Materials – Summary

R&D suggests that there is a pathway to acceptable material life

- **Ferritic and austenitic steels perform well at or below 400°C**
- **Higher alloyed Fe- and Ni-based steels perform well up 600°C**
- **Ni-based alloys most promising for > 700°C**
- **Future work**
  - Longer term testing for corrosion
  - Additional evaluation of O_2 and H_2O effects
  - Additional mechanical testing (creep and fatigue) in sCO_2 environment
  - Evaluate materials specifically for recuperator applications (creep, fatigue, corrosion, bonding)
  - Higher temperature (≥800°C) testing for direct-fired cycles

Materials Limit the Current Technology



Source: EPRI, Project FE0025064 “Materials for Advanced Ultra-supercritical Steam Turbines – Advanced Ultra-supercritical Component Demonstration” NETL 2017 Crosscutting Research Project Review Meeting, March 23, 2017, Pittsburgh, PA.

Other sCO_2 Cycle Considerations

- **The sCO_2 cycle is more sensitive to ambient temperature for cooling (compared to steam Rankine)**
  - sCO_2 not condensing (no phase change) in the cooler
  - Directly affects cold sCO_2 temperature and the power required for compression
  - Impacts sCO_2 cycle efficiency
- **Higher mass flows in sCO_2 cycle vs steam cycle**
  - Pipe size (cross-sectional area) increases for sCO_2 cycle
    - Steam boilers can handle higher pressure drops and velocities
    - Molar specific heats for steam comparable or higher than for sCO_2 at a given temperature
    - High recuperation of heat to the returning sCO_2 yields a smaller ΔT for heat addition
    - sCO_2 boiler and steam boiler at same T, P, and heat duty » then $Q_{steam} = Q_{sCO2}$

$$\mathbf{(V*A*\bar{C}p*\Delta T)_{steam} = (V*A*\bar{C}p*\Delta T)_{sCO2}}$$

    - Pressure ratio across the turbine affects higher sCO_2 mass flow
    - Overall, the sCO_2 power cycle is more sensitive to pressure drop than the steam cycle

Presentation Outline

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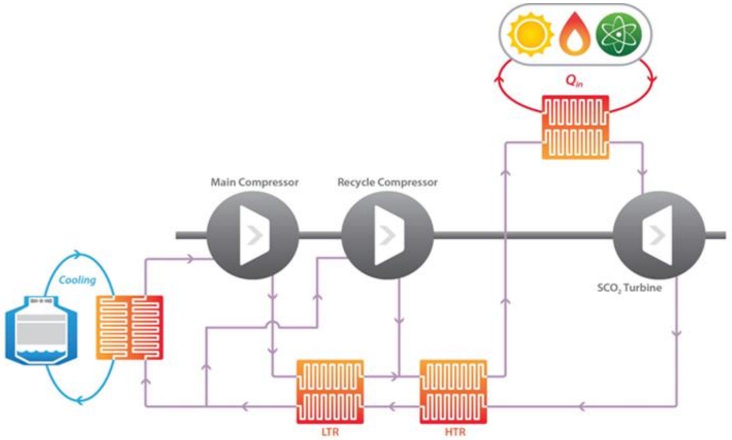
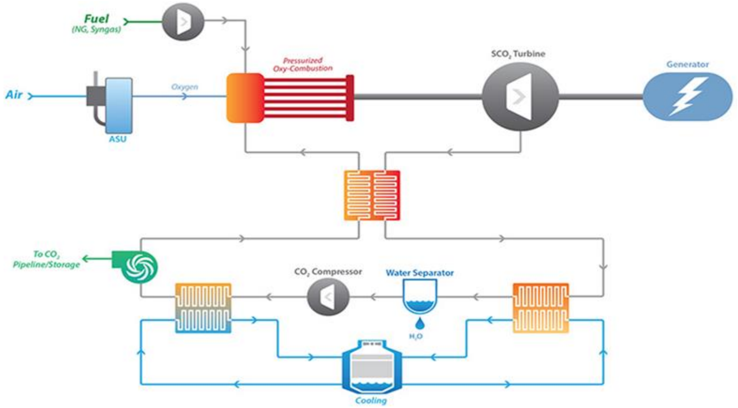


Indirectly-heated cycle



Directly-heated cycle

FE Project Activities in sCO_2 Based Power Cycles

Turbomachinery for Indirect and Direct sCO_2 Power Cycles

- Low-leakage shaft end seals for sCO_2 turbomachinery (**GE**)
- Adv. turbomachinery for sCO_2 cycles (**Aerojet Rocketdyne**) (complete)

Oxy-Fuel Combustors for sCO_2 Power Cycles

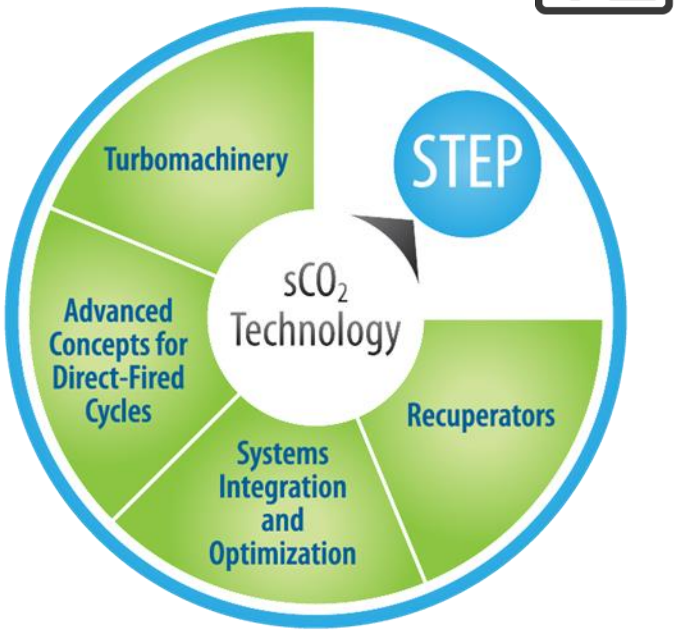
- HT combustor for direct fired supercritical oxy-combustion (**SwRI**)
- Oxy fuel combustion (**NETL**)
- Autoignition and combustion stability of high pressure sCO_2 oxy-combustion (**GA Tech**)
- Chemical kinetic modeling and experiments for direct fired sCO_2 Combustor (**UCF**)
- Coal syngas comb. for HP oxy-fuel sCO_2 cycle (**8 Rivers Capital**) (complete)

Recuperators for sCO_2 Power Cycles

- Microchannel HX (**Oregon State U**)
- Low-cost recuperative HX (Altex Tech. Corp) (complete)
- Mfg. process for low-cost HX applications (**Brayton Energy**) (complete)
- HT HX for systems with large pressure differentials (**Thar Energy**) (complete)
- Thin film primary surface HX (**SwRI**) (complete)

Materials, Fundamentals and Systems

- R&D materials & systems analyses (**NETL**)
- Oxidation/corrosion performance of alloys in sCO_2 (**EPRI**)
- Advanced materials for supercritical carbon dioxide (**ORNL**)
- Thermophysical properties of sCO_2 (**NIST**) (complete)



sCO_2 Heater Integration

- Thermal integration of closed sCO_2 power cycles with oxy-fired heaters (**EPRI**)
- Novel indirect sCO_2 power cycle for integration of secondary and thermal systems with the power block (**SwRI**)

STEP

- Development of advanced recuperators (**Thar Energy**)
- Design, build, and operate 10MWe STEP pilot facility (**GTI**)

Supercritical Carbon Dioxide 10 MWe Pilot Plant Test Facility

Gas Technology Institute

Objectives

- Plan, design, build, and operate a 10 MWe sCO_2 Pilot Plant Test Facility
- Demonstrate the operability of the sCO_2 power cycle
- Verify performance of components (turbomachinery, recuperators, compressors, etc.)
- Evaluate system and component performance capabilities
  - Steady state, transient, load following, limited endurance operation
- Demonstrate potential for producing a lower COE and thermodynamic efficiency greater than 50%

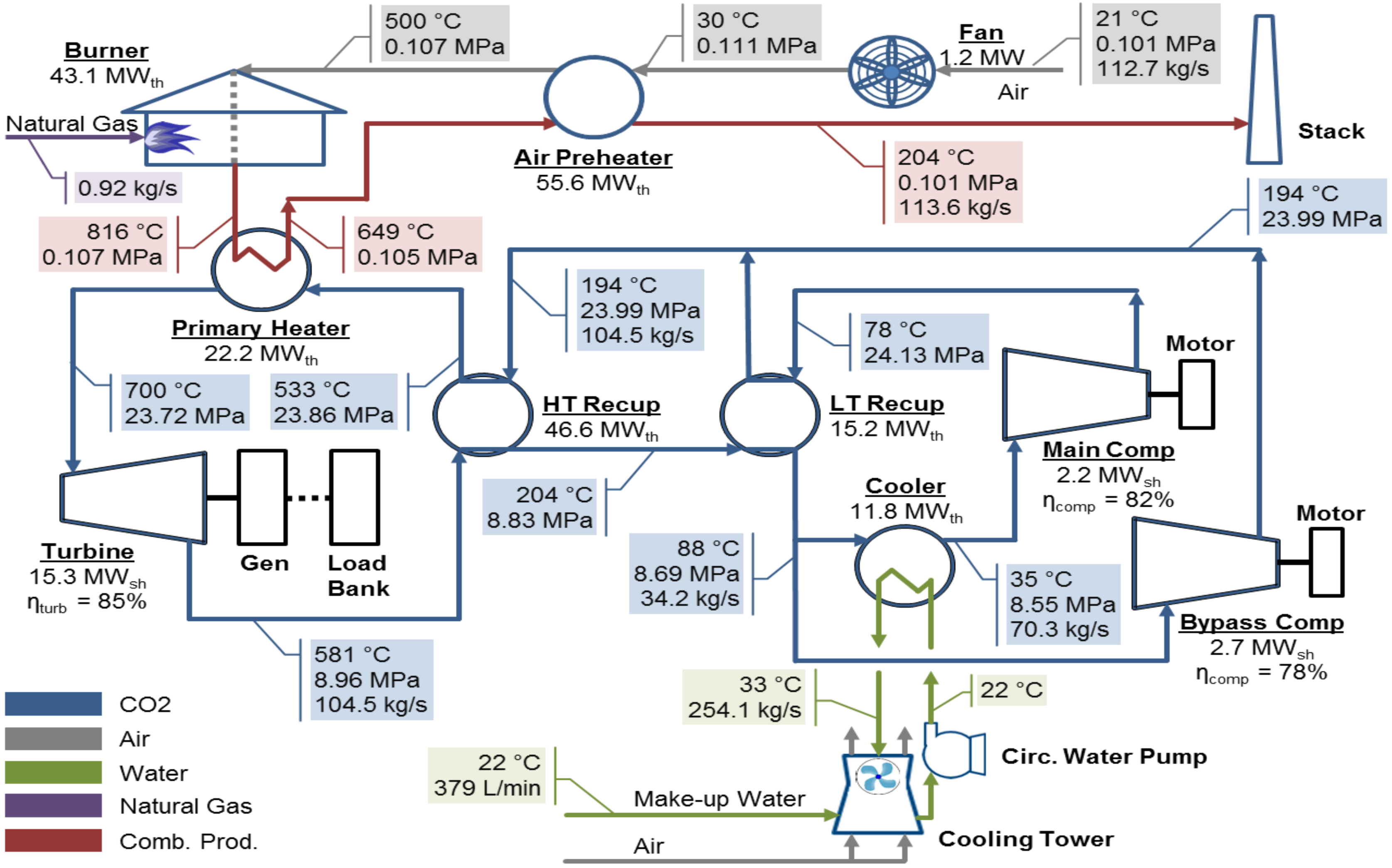
GAS TECHNOLOGY INSTITUTE

FE0028979
Partners: SwRI, GE Global Research
10/1/2016 – 9/30/2022

BUDGET		
DOE	*Participant*	*Total*
$79,999,226	$33,279,408	$113,278,634

Baseline 700°C 10 MWe RCB Cycle Diagram

NETL Basis for Cost Estimate of STEP Facility (similar to what will be built)



Source: “10 MW sCO_2 Pilot Plant Techno-economic Analysis – Variations”, NETL June 26, 2015

Recompression Closed Brayton Cycle Test Article (TA) at Sandia National Laboratories (DOE NE)

TA Description:

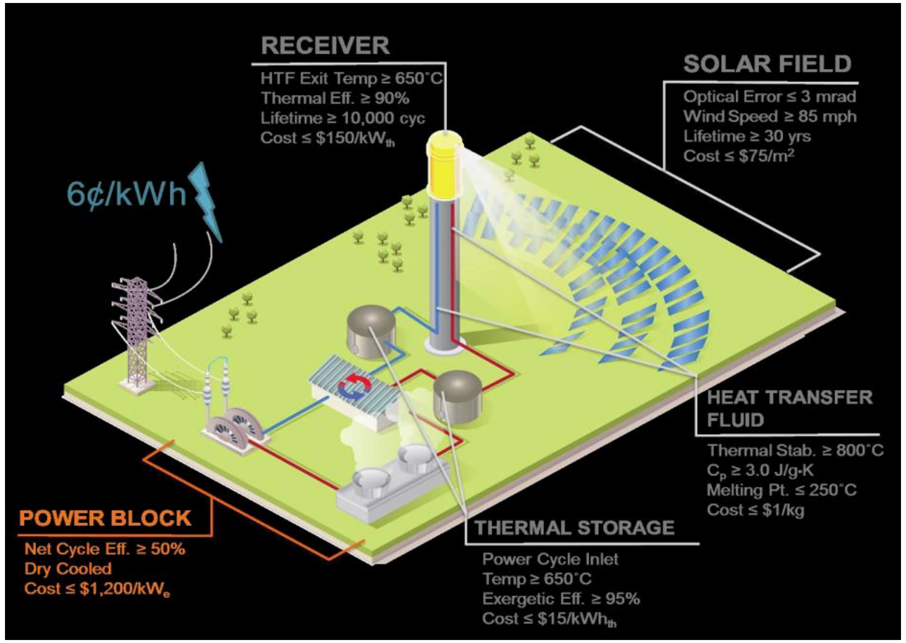
Heater – 750 kW, 550°C
Max Pressure - 14 MPa
2 power turbines, 2 compressors
High Temp Recuperator - 2.3 MW duty
ASME B31.1 Coded Pipe, 6 Kg/s flow rate
Low Temp Recuperator – 1.7 MW duty
Gas Chiller – 0.6 MW duty

- TA under test since 4/2010
- Over 100 kW-hrs of power generated
- Operated in 3 configurations
  - Simple Brayton
  - Waste Heat Cycle
  - Recompression
- Verified cycle performance
- Developed Cycle Controls
- Developing maintenance procedures

DOE EERE Sunshot Project

Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP sCO2 Operation

- Develop high-efficiency sCO2 turbo-expander optimized for solar transients
  - Advances the SOTA TRL from 3 to 6
- Optimize recuperator for sCO2 applications
- Turbo-expander & HX tested in a 1-MWe sCO2 loop
- Close technology gaps required for an optimized concentrating solar power (CSP) sCO2 plant and provide a major stepping stone on the pathway to achieving CSP at $0.06/kW-hr levelized cost of electricity (LCOE), increasing energy conversion efficiency to greater than 50%, and reducing total power block cost to below $1200/kW installed



Echogen Power Systems

World's leader in sCO_2 based WHR applications

- Leader in waste heat recovery (WHR) applications based on carbon dioxide as the working fluid
- Systems ready for commercial application
  - Currently up to 8 MW offerings
- Ideally suited for WHR bottoming cycles on small scale combustion turbines

EPS100 sCO2 heat engine, process and power skids (1)

Ref 1: SUPERCRITICAL CO2 CYCLES FOR GAS TURBINE COMBINED CYCLE POWER PLANTS, T. Held, Power Gen International December 8-10, Las Vegas, Nevada

NET POWER's
25 MWe Direct Fired SCO2 Power Plant

Net Power's 25 MWe Allam cycle based power plant in La Port, TX; circa spring 2017 (a privately funded project).

Photographs by permission of Net Power

Construction Status

- Construction over 90% complete
- Commissioning various subsystems
  - Cooling water
  - turbine lube oil
- Combustor operation in the fall '17
- Targeting grid connection in 2018

Summary and Conclusions

Overview of Supercritical Carbon Dioxide Based Power Cycles
for Stationary Power Generation

- **Power cycles based on sCO_2 offer benefits to stationary power production**
  - RCB cycle for CSP, nuclear on fossil energy heat sources
  - Allam cycle offers benefits to gaseous carbon based fuels with CO_2 capture
- **DOE's sCO_2 CCI and the Offices of FE, NE and EERE have invested significantly to develop sCO_2 power cycle technology**
- **Projects are resolving technical issues (public and private investment)**
- **Technical issues remain**
  - Materials
  - Heat source power cycle integration
  - Component development, optimization and demonstration (turbines, compressors and recuperators)
  - Cycle performance and cost

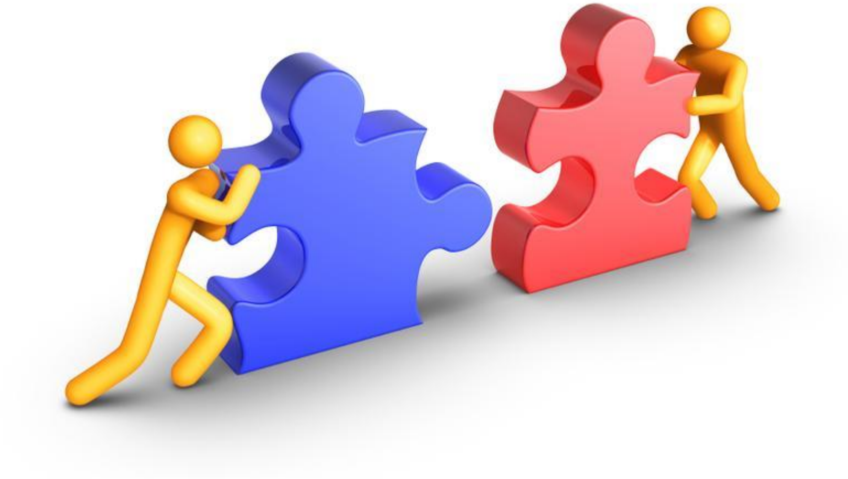
DOE Team Work

Team Work Makes This Program Possible

- **NETL Team: N. Weiland, C. White, W. Shelton, T. Shultz, P. Strakey, S. Lawson, R. Ames, H. Quedenfeld, G. Jesionowski, D. Harkreader, O. Dogan**

- **DOE Crosscut Initiative Team: D. Mollot (FE), B. Sastri (FE), R. Conrad (FE), S. Golub (NE), B. Robinson (NE), A. Shultz (EERE), M. Lausten (EERE), R. Vijaykumar (EERE), M. Bauer (EERE)**

- **Significant contributions from the US National Laboratory complex including Sandia National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, National Energy Technology Laboratory and Argonne National laboratory**



Backup Slides

Development of Low-Leakage Shaft End Seals for Utility-Scale sCO_2 Turbo Expanders

General Electric Co.

NATIONAL ENERGY TECHNOLOGY LABORATORY

PROJECT NARRATIVE

- Develop expander shaft end seals for utility-scale sCO_2 power cycles
- Conceptual design of a utility scale end seal capable of meeting the component-level and system-level objectives
- Thermodynamic optimization and preliminary design for a conceptual layout for a utility-scale sCO_2 power plant
- Develop face seals as a solution for end shaft sealing for sCO_2 turbo expanders
- Conceptual design of sCO_2 test rig

Phase II

- Design/fabrication of sCO_2 utility-scale test rig to evaluate end seals
- Testing of utility-scale end seals on test rig at relevant operating conditions
- Development of radial seals for turbo expanders

BENEFITS

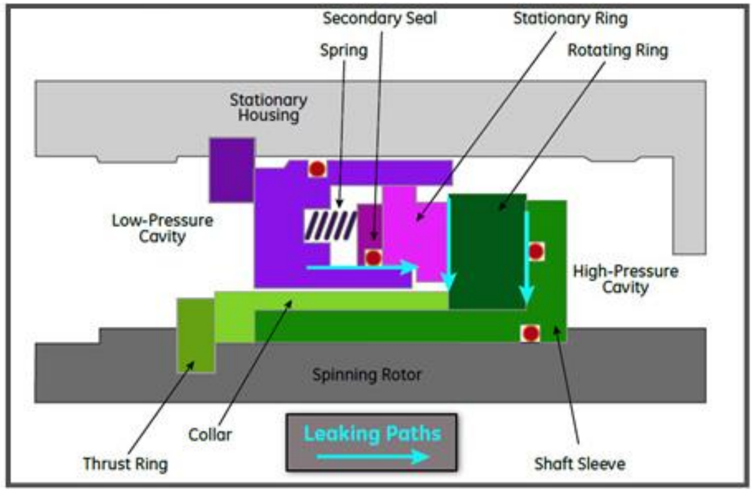
- Enables transformational goal of $10/metric ton CO_2 capture by 2035
- Thermodynamic cycle efficiencies of 50-52 percent or greater
- Reduced water consumption, reduced power block size and better thermodynamic integration with post-combustion CO_2 capture equipment

GENERAL ELECTRIC CO.

FE0024007
Partners: SwRI
10/1/2014 – 8/31/2019

BUDGET

DOE	*Participant*	*Total*
$6,824,098	$1,793,304	$8,617,402



Dry Gas Sealing Technology

High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion

Southwest Research Institute

PROJECT NARRATIVE

- The project team seeks to develop a high inlet temperature oxy-combustor suitable for integration with direct-fired supercritical CO_2 power cycles for fossil energy applications
- R&D evaluation of direct-fired sCO_2 oxy-combustor has involved system engineering design and thermodynamic analysis to assess plant efficiencies, verify operating conditions and optimize plant configuration in conjunction with technical gap analysis
- The Phase II effort seeks to build a ‘first-of-a-kind’ 1 MW test facility in order to evaluate the sCO_2 oxy-combustor technology in an integrated system (which enables both component- and system-level testing) to address/reduce technical uncertainties

BENEFITS

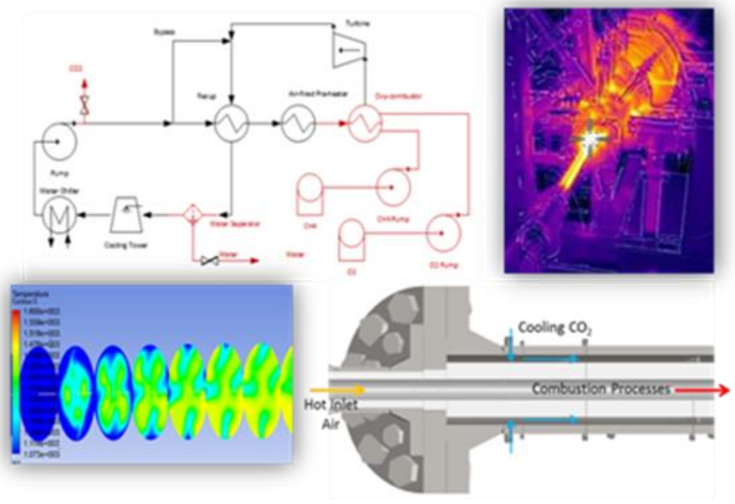
- Efficient power generation with integrated carbon capture at up to 99 % of generated CO_2
- Advances state-of-the-art in high pressure, high temperature combustor design

SOUTHWEST RESEARCH INSTITUTE

FE0024041
Partners: Thar Energy, GE Global Research,
U. of Central Florida, Georgia Tech
10/1/2014 - 3/31/2020

BUDGET

DOE	*Participant*	*Total*
$3,793,540	$948,404	$4,741,944



Direct Fired Supercritical CO_2 Oxy-Combustion: Bench Scale Testing and 1MW Scale Concept

Technology Development of Modular, Low-Cost, High-Temperature Recuperators for sCO_2 Power Cycles

Thar Energy

Project Goals/Objectives

- **Recuperator development plans for multiple high temperature recuperator concepts (indirect-fired sCO_2 power cycle)**
  - **BP1**: Concept Evaluation and Down Select
    - Engineering analyses of concepts – ***COMPLETE***
      - Critical enabling technologies or components
      - Manufacturability
      - Potential nth of a kind production cost
      - Anticipated performance
    - Down select most promising concepts - ***COMPLETE***
    - Design, fabricate and test 100 kWth recuperators of down selected concepts
  - **BP2**
    - Down select final recuperator concept
    - Detailed design, fabrication of recuperator sized (47 MWth) for 10 MWe pilot plant

THAR ENERGY

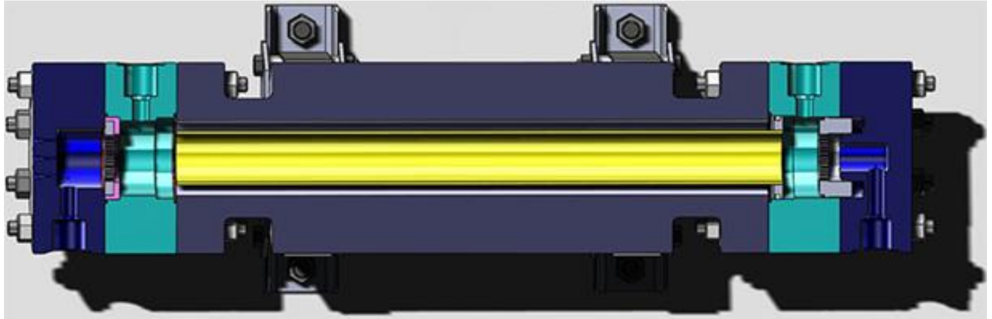
FE0026273

Partners: SwRI, ORNL, Georgia Tech

10/1/2015 – 3/31/2019

BUDGET

DOE	*Participant*	*Total*
$9,344,826	$2,348,709	$11,693,535



Microtubular Heat Exchanger Concept

Investigation of Autoignition and Combustion Stability of High Pressure Supercritical Carbon Dioxide Oxycombustion

Georgia Tech Research Corporation

PROJECT NARRATIVE

- Perform fundamental R&D on combustion kinetics and dynamics at supercritical CO_2 power cycle operating conditions for natural gas and syngas oxy-combustion.
- Focus on knowledge gaps for sCO_2 oxy-combustion at high pressure including fundamental autoignition properties, development of chemical kinetic mechanism, and numerical and theoretical analyses of flow, mixing, and flame dynamics.
- Study of flame stability based on newly developed kinetic mechanism.
- Integration of experimental, numerical, and theoretical efforts.

BENEFITS

- Experimental data generated for autoignition, combustion dynamics, and flame dynamics used to validate a chemical kinetic mechanism at sCO_2 conditions to facilitate sCO_2 combustor designs.

GEORGIA TECH		
FE0025174 *10/1/2015 - 9/30/2018*		
BUDGET		
DOE	*Participant*	*Total*
$799,754	$320,767	$1,120,521

Shock-tube for Autoignition Study

Chemical Kinetic Modeling Development and Validation Experiments for Direct Fired Supercritical Carbon Dioxide Combustor

University of Central Florida

PROJECT NARRATIVE

- A chemical kinetic model will be created for sCO_2 oxy-methane combustion based on reaction rate calculations and updating current mechanism.
- Model will be validated using two different shock tube facilities to cover pressures up to 300 bar.
- Experiments will include both ignition delay times and species time-histories using absorption spectroscopy.
- A CFD code will be created in OpenFOAM to utilize the chemical kinetic mechanism for direct fired sCO_2 combustor designs.

BENEFITS

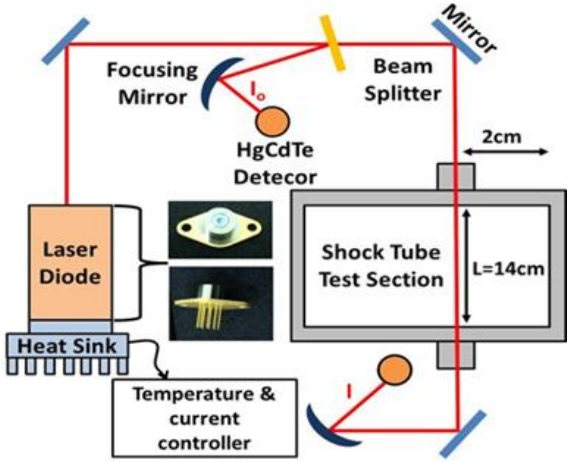
- Direct-fired sCO_2 power cycles offer many advantages to the current state-of-the-art, including improvements in the thermal efficiency, reduced size of energy systems, low costs and 99% carbon capture. A new, advanced model will be established for design of future combustors.

UNIVERSITY OF CENTRAL FLORIDA

FE0025260
Partners: Stanford University; Embry-Riddle Aeronautical University
10/1/2015 - 9/30/2018

BUDGET

DOE	*Participant*	*Total*
$800,000	$302,793	$1,102,793



Experimental Setup for Validation Testing

High Efficiency Thermal Integration of Supercritical CO_2 Brayton Power Cycles for Oxy-Fired Heaters

Electric Power Research Institute

PROJECT NARRATIVE

- Develop process designs and cost estimates for test cases that optimally integrate closed supercritical carbon dioxide (sCO_2) power cycles with oxy/coal-fired heater
- Identify technology gaps in the sCO_2 Brayton power cycle plants
- Identify components whose cost might be reduced by focused R&D

BENEFITS

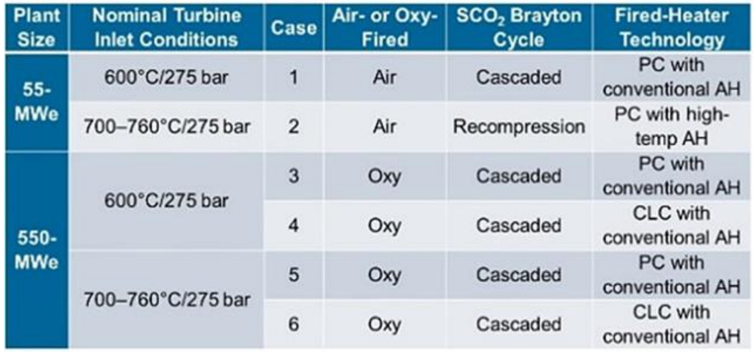
- Oxy/coal-fired sCO_2 Brayton cycle power plants with the potential to increase efficiency by 3 to 5 percentage points

EPRI

FE0025959
Partners: Alstom Power Inc, Babcock & Wilcox Power Generation Group, Doosan America ATS, Echogen Power Systems, Howden Group
10/1/2015 - 9/30/2017

BUDGET

DOE	*Participant*	*Total*
$1,838,062	$459,516	$2,297,578



Plant Size	Nominal Turbine Inlet Conditions	Case	Air- or Oxy-Fired	SCO_2 Brayton Cycle	Fired-Heater Technology
55-MWe	600°C/275 bar	1	Air	Cascaded	PC with conventional AH
	700–760°C/275 bar	2	Air	Recompression	PC with high-temp AH
550-MWe	600°C/275 bar	3	Oxy	Cascaded	PC with conventional AH
		4	Oxy	Cascaded	CLC with conventional AH
	700–760°C/275 bar	5	Oxy	Cascaded	PC with conventional AH
		6	Oxy	Cascaded	CLC with conventional AH

Summary of Test Cases to Be Studied

An Advanced Gas Foil Bearing Using Supercritical Carbon Dioxide as the Working Fluid

Mechanical Solutions, Inc.

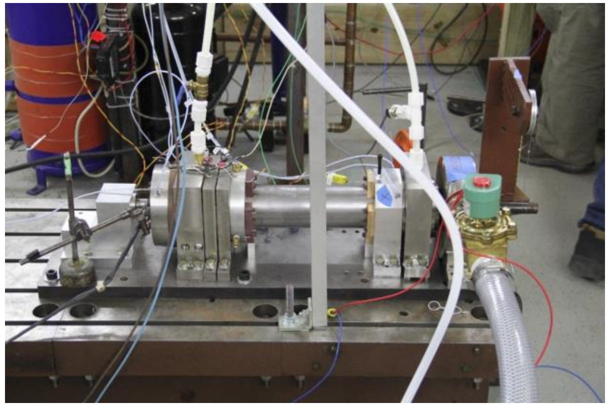
PROJECT NARRATIVE

- Phase II SBIR Project
- Develop reliable, high performance foil bearing system for sCO_2 power cycle machinery
- Capable of T up to 800°C and P up to 300 bar
- Design both radial bearings and thrust bearings
- Update analytical models to include sCO_2 fluid properties, evaluate bump foil geometries and patterns to maximize load carrying capacity, evaluate candidate coatings for start-stop wear resistance
- Designs will be combined for validation testing of wear coatings, hydrostatic strategy, and bumper designs

BENEFITS

- Advanced foil bearing design enables development of more efficient sCO_2 power cycle machines with higher turbine inlet temperatures and pressures

Mechanical Solutions, Inc.		
SC0013691		
6/8/2015 - 7/31/2018		
Budget		
DOE	Participant	Total
$1,148,610	$0	$1,148,610



MSI's High Speed Foil Bearing Test Rig

sCO$_2$ Power Cycles

US Government Development History

NE begins evaluation of sCO$_2$ cycle

1st Symposium on sCO$_2$ Power Cycles

SNL sCO$_2$ RCBC 250 kWe test loop begins

EERE begins SunShot Initiative

Bettis begins sCO$_2$ Brayton Cycle Integrated System Test

FE begins projects on sCO$_2$ power cycle

NETL, SNL, NREL sCO$_2$ workshop (SwRI)

DOE Collaboration on sCO$_2$ begins forming the NE, EE, FE DOE Crosscut Initiative

FE Phase I oxy-combustion projects begin

FE recuperator projects begin

FE Phase I turbomachinery projects begin

NE RFP award on cost, design, technical approach of 10 MWe facility

STEP advanced recuperator project begins

STEP facility design & build FOA issued

Phase II projects in turbomachinery and oxy-combustion selected

ABBREVIATION KEY:

NE:	Nuclear Energy
FE:	Fossil Energy
EERE:	Energy Efficiency and Renewable Energy
SNL:	Sandia National Laboratories
SwRI:	Southwest Research Institute
RFP:	Request for Proposals
STEP:	Supercritical Transformational Electric Power
RCBC:	Recompression Closed Brayton Cycle
FOA:	Funding Opportunity Announcement
NREL:	National Renewable Energy Laboratory

sCO_2 Power Cycles

Conferences, Symposia, and Workshops

03.06.07
1st Symposium on sCO_2 Power Cycle (MIT, Boston, MA)

04.29.09
2nd sCO_2 Power Cycle Symposium (RPI, Troy, NY)

03.24.11
sCO_2 Property Data Needs Workshop (NETL, EPRI sponsored, Pittsburgh, PA)

05.24.11
3rd sCO_2 Power Cycle Symposium (University of CO, Boulder, CO)

06.11.12
ASME Turbo Expo - sCO_2 Track (Copenhagen, Denmark)

02.01.13
sCO_2 Power Cycle Technology Roadmapping Workshop (SwRI, San Antonio, TX)

06.03.13
ASME Turbo Expo - sCO_2 Track (San Antonio, TX)

06.16.14
ASME Turbo Expo - sCO_2 Track (Dusseldorf, Germany)

06.23.14
sCO_2 Power Cycle Development Workshop (DOE sCO2 CCI team), (Washington DC)

09.09.14
4th International Symposium on sCO_2 Power Cycles (Pittsburgh, PA)

09.11.14
sCO_2 Brayton Cycle Energy Conversion R&D Workshop (DOE sCO2 CCI team), (Pittsburgh, PA)

06.19.15
ASME Turbo Expo - sCO_2 Track (Montreal, Canada)

10.15.15
EPRI-NETL Workshop on Heat Exchangers for sCO_2 Power Cycles (San Diego, CA)

03.29.16
5th International sCO_2 Power Cycles Symposium (San Antonio, TX)

06.13.16
ASME Turbo Expo - sCO_2 Track (Seoul, South Korea)

06.13.17
ASME Turbo Expo - sCO_2 Track (Charlotte, NC)

03.27.18
6th International sCO_2 Power Cycles Symposium (Pittsburgh, PA)

06.TBD.18
ASME Turbo Expo -sCO_2 Track (Oslo, Norway)

ABBREVIATION KEY:

SCO_2:	Supercritical Carbon Dioxide
MIT:	Massachusetts Institute of Technology
RPI:	Rensselear Polytechnic Institute
SwRI:	Southwest Research Institute
ASME:	American Society of Mechanical Engineers
EPRI:	Electric Power Research Institute

DOE SCO_2 CCI Team: Department of Energy Supecritical Carbon Dioxide Crosscut Initiative Team

sCO_2 Power Cycles

Key Literature

04.01.67
Angelino - fluids other than air can be used in CBC

01.13.68
Feher - advantages of supercritical cycles

07.01.68
Angelino - recompression CBC with CO_2 gives superior efficiencies to steam > 550°C

02.01.76
GE - study of advanced energy systems, including sCO_2 power cycle

03.10.04
Dostal - evaluations of sCO_2 power cycles for nuclear applications

04.29.09
NREL - sCO_2 power cycles in CSP

05.24.11
Heatric - mechanical design issues in PCHE

04.20.12
Echogen - waste heat recovery system using sCO_2 cycle instead of steam

06.11.12
Barber-Nichols - guidelines for turbomachinery selection for sCO_2 cycles

06.11.12
Pratt & Whitney Rocketdyne (GTI) - ZEPS^{TM} plant with pressurized fluidized bed indirect sCO_2 cycle

10.01.12
SNL - development of sCO_2 test loop

10.30.12
Anderson (U of Wisconsin) - materials, turbomachinery, and heat exchangers for sCO_2 systems

01.01.13
Allam - direct Allam cycle for 50 MWth demo facility

01.01.13
Moullec - study of coal-fired plant with sCO_2 Brayton cycle

02.01.13
EPRI - program on Brayton cycle for coal-fired power plants

06.03.13
ORNL, EPRI - material considerations for sCO_2 cycle

09.09.14
BMPC - development/operation of sCO_2 test loop

09.09.14
GE, SwRI - turbo-expander for sCO_2 CSP application

09.09.14
BMPC, Brayton Energy - testing recuperators in sCO_2 test loop

12.15.14
EPRI - performance and economic evaluation of sCO_2 coal gasification plant

06.15.15
SwRI - evaluation of sCO_2 cycles for oxy-combustion

03.29.16
NETL - performance baseline for direct-fired sCO_2 cycles

03.29.16
GE - conceptual designs of 50 and 450 MWe sCO_2 turbomachinery trains

06.01.16
DOE QTR 2015 - Technology Assessment of sCO_2 Brayton Cycle

ABBREVIATION KEY:

sCO_2:	supercritical carbon dioxide	NETL:	National Energy Technology Laboratory
CBC:	closed Brayton cycle	CSP:	concentrating solar power
GE:	General Electric	DOE:	Department of Energy
NREL:	National Renewable Energy Laboratory	QTR:	Quadrennial Technology Review
ZEPS^{TM}:	Zero Emissions Power and Steam	GTI:	Gas Technology Institute
ORNL:	Oak Ridge National Laboratory	SNL:	Sandia National Laboratories
BMPC:	Bechtel Marine Propulsion Corporation	PCHE:	printed circuit heat exchanger
SwRI:	Southwest Research Institute	EPRI:	Electric Power Research Institute

sCO_2 Power Cycle – Key Literature

References

DATE	MILESTONE	REFERENCE
04.01.67	Angelino - fluids other than air can be used in CBC	Angelino, G., "Perspectives for the liquid phase compression gas turbine," Journal of Engineering for Power 89, No. 2 (1967) 229-237.
01.13.68	Feher - advantages of supercritical cycles	Feher, E., "The supercritical thermodynamic power cycle," Energy Conversion 8 (1968) 85-90.
07.01.68	Angelino - recompression CBC with CO_2 gives superior efficiencies to steam > 550°C	Angelino, G., "Carbon dioxide condensation cycles for power production," Journal of Engineering for Power (1968) 287-295 (ASME paper 68-GT-23).
02.01.76	GE - study of advanced energy systems, including sCO_2 power cycle	"Energy Conversion Alternatives Study - ECAS," NASA-CR 134948 vol 1 & 2, February 1976.
03.10.04	Dostal - evaluations of sCO_2 power cycles for nuclear applications	Dostal, V., et al., "A supercritical carbon dioxide cycle for next generation nuclear reactors," MIT-NAP-TR-100 3/10/2004.
04.29.09	NREL - sCO_2 power cycles in CSP	Turchi, C., "Supercritical CO_2 for application in concentrating solar power systems," Proceedings of the Supercritical CO_2 Power Cycle Symposium, Troy, NY, April 29-30, 2009.
05.24.11	Heatric - mechanical design issues in PCHE	Le Pierres, R., et al., "Impact of mechanical design issues on printed circuit heat exchangers," Proceedings of sCO_2 Power Cycles Symposium, Boulder, CO, May 24-25, 2011.
04.20.12	Echogen - waste heat recovery system using sCO_2 cycle instead of steam	Held, et al., "Supercritical CO_2 power cycle developments and commercialization: why sCO_2 can displace steam," PowerGen India & Central Asia 2012, New Delhi, India, April 19-21, 2012.
06.11.12	Pratt & Whitney Rocketdyne (GTI) - ZEPS^{TM} plant with pressurized fluidized bed indirect sCO_2 cycle	Subbaraman, G. et al., "Supercritical CO_2 cycle development at Pratt & Whitney Rocketdyne," GT2012-70105, Proceedings of ASME Turbo Expo 2012, Copenhagen, Denmark, June 11-15, 2012.
06.11.12	Barber-Nichols - guidelines for turbomachinery selection for sCO_2 cycles	Fuller, et al. "Turbomachinery for supercritical CO_2 power cycles," GT2012-68735, Proceedings of ASME Turbo Expo 2012, Copenhagen, Denmark, June 11-15, 2012.
10.01.12	SNL - development of sCO_2 test loop	Pasch, J., et al., "Supercritical CO_2 Recompression Brayton cycle: Completed Assembly Description," Sandia National Laboratories Report SAND2012-9546, October 2012.
10.30.12	Anderson (U of Wisconsin) - materials, turbomachinery, and heat exchangers for sCO_2 systems	Anderson, M., "Materials, turbomachinery and heat exchangers for supercritical CO_2 systems," Nuclear Energy University Programs Final Report Project No. 09-778, October 30, 2012. (University of Wisconsin, collaboration with Sandia National Laboratory)

sCO$_2$ Power Cycle – Key Literature

References *(cont.)*

DATE	MILESTONE	REFERENCE
01.01.13	Allam - direct Allam cycle for 50 MW$_{th}$ demo facility	Allam, R., et al., "High efficiency and low cost of electricity generation form fossil fuels while eliminating atmospheric emissions, including carbon dioxide," Energy Procedia 37 (2013) 1135-1149
01.01.13	Moullec - study of coal-fired plant with sCO$_2$ Brayton cycle	Moullec, Y., "Conceptual study of a high efficiency coal-fired power plant with CO$_2$ capture using a supercritical CO$_2$ Brayton cycle," Energy 49 (2013) 32-46.
02.01.13	EPRI - program on Brayton cycle for coal-fired power plants	"Program on Technology Innovation: Modified Brayton Cycle for Use in Coal-Fired Power Plants," EPRI, Palo Alto, CA: 2013. 1026811
06.03.13	ORNL, EPRI - material considerations for sCO$_2$ cycle	Pint, B., et al., "Materials considerations for supercritical CO$_2$ turbine cycles," GT2013-94941, Proceedings of ASME Turbo Expo 2013 , San Antonio, TX, June 3-7, 2013.
09.09.14	BMPC - development/operation of sCO$_2$ test loop	Clementoni, E. and Cox, T., "Practical aspects of supercritical carbon dioxide Brayton system testing,"Proceedings of the 4th International Symposium - Supercritical CO$_2$ Power Cycles, Pittsburgh, PA, September 9-10, 2014.
09.09.14	GE, SwRI - turbo-expander for sCO$_2$ CSP application	Moore, J. et al., "Development of high efficiency hot gas turbo-expander for optimized CSP supercritical CO$_2$ power block operation," Proceedings of the 4th International Symposium - Supercritical CO$_2$ Power Cycles, Pittsburgh, PA, September 9-10, 2014.
09.09.14	BMPC, Brayton Energy - testing recuperators in sCO$_2$ test loop	Fourspring, P. et al., "Testing of compact recuperators for a supercritical CO$_2$ Brayton power cycle," Proceedings of the 4th International Symposium - Supercritical CO$_2$ Power Cycles, Pittsburgh, PA, September 9-10, 2014.
12.01.14	EPRI - performance and economic evaluation of sCO$_2$ coal gasification plant	"Performance and Economic Evaluation of Supercritical CO$_2$ Power Cycle Coal GasificationPlant," EPRI, Palo Alto, CA: 2014. 3002003734
06.15.15	SwRI - evaluation of sCO$_2$ cycles for oxy-combustion	McClung, A., et al., "Comparison of supercritical carbon dioxide cycles for oxy-combustion," GT2015-42523, Proceedings of Turbo Expo 2015, Montreal, Canada, June 15-19, 2015.
03.29.16	NETL - performance baseline for direct-fired sCO$_2$ cycles	Weiland, N., et al., "Performance baseline for direct-fired sCO$_2$ cycles," Proceedings of the 5th International Symposium - Supercritical CO$_2$ Power Cycles, San Antonio, TX, March 29-31, 2016.
03.29.16	GE - conceptual designs of 50 and 450 MWe sCO$_2$ turbomachinery trains	Bidkar, R., et al., "Conceptual Designs of 50 MWe and 450 MWe Supercritical CO$_2$ Turbomachinery Trains for Power Generation from Coal. Part 1: Cycle and Turbine," Proceedings of the 5th International Symposium - Supercritical CO$_2$ Power Cycles, San Antonio, TX, March 29-31, 2016.
06.01.16	DOE QTR 2015 - Technology Assessment of sCO$_2$ Brayton Cycle	DOE Quadrennial Technology Review 2015 (September 2015), Supplemental section (June 2016) Technology Assessments, Chapter 4R: "Supercritical Carbon Dioxide Brayton Cycle"

Supercritical CO_2 Power Cycle Application Space

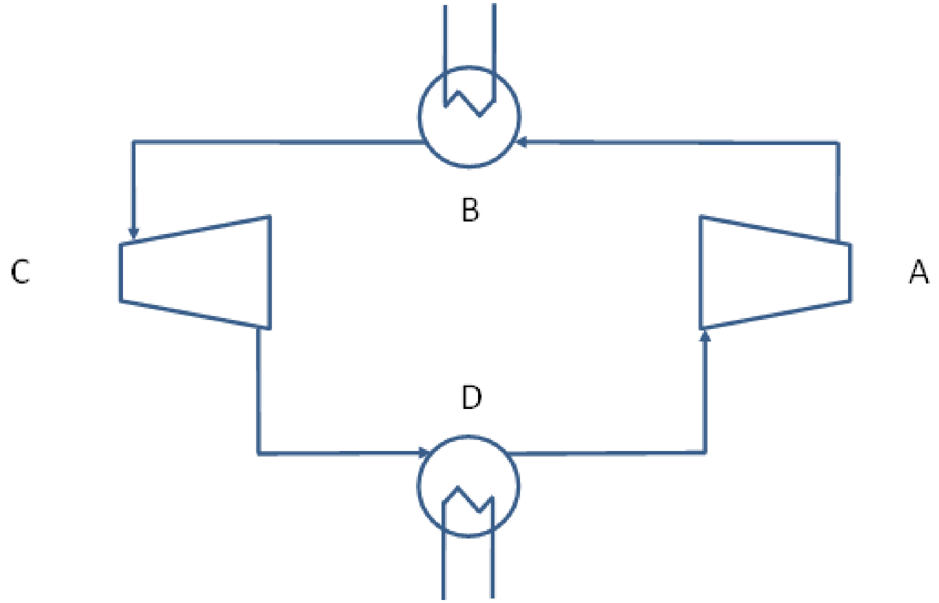
Application	Size [MWe]	Temperature [°C]	Pressure [MPa]
Nuclear (NE)	10 – 300	350 – 700	20 – 35
Fossil Fuel (FE) (Indirect heating)	300 – 600	550 – 900	15 – 35
Fossil Fuel (FE) (Direct heating)	300 – 600	1100 – 1500	35
Concentrating Solar Power (EERE)	10 – 100	500 – 1000	35
Shipboard Propulsion	10 – 100	500 – 1000	35
Shipboard House Power	<1 – 10	230 – 650	15 - 35
Waste Heat Recovery (FE)	1 – 10	< 230 – 650	15 – 35
Geothermal (EERE)	1 – 50	100 – 300	15

Diverse fuel/heat sources:

Coal, natural gas, nuclear, solar, waste heat, geothermal, propulsion applications

Simple Cycle

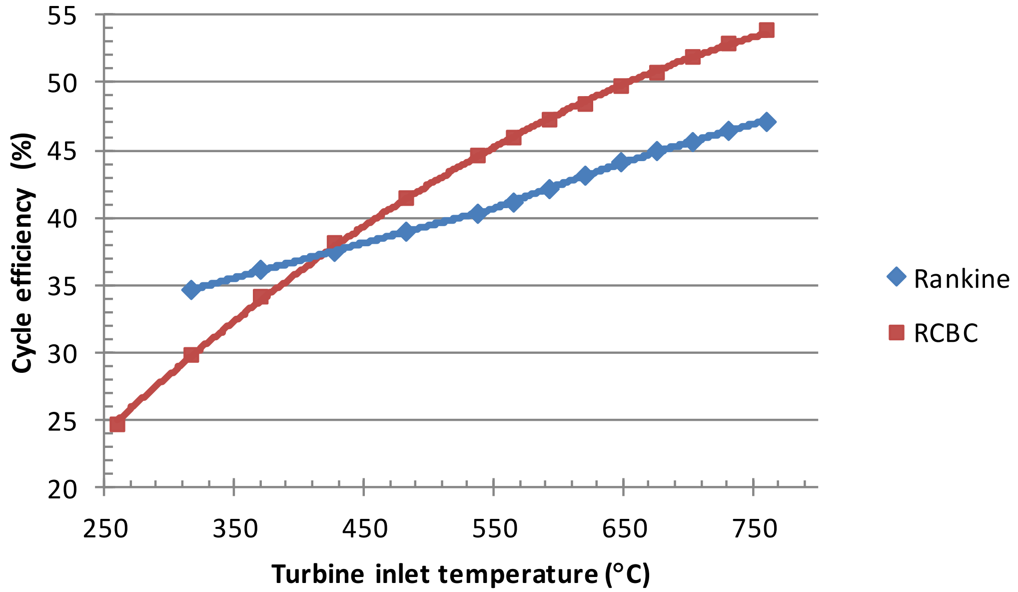
- **Ideal cycle**
  - Ideal gas
  - No irreversibility
  - Cycle efficiency depends only on cycle pressure ratio (increases with PR)
- **Non-ideal cycle**
  - Real gas
  - Cycle efficiency passes through a max depending on fluid
  - Cycle efficiency with CO_2 strongly dependent on minimum cycle pressure



Overview sCO_2 Power Cycles

Supercritical CO_2 Recompression Brayton Cycle (RCBC) versus Rankine Cycle

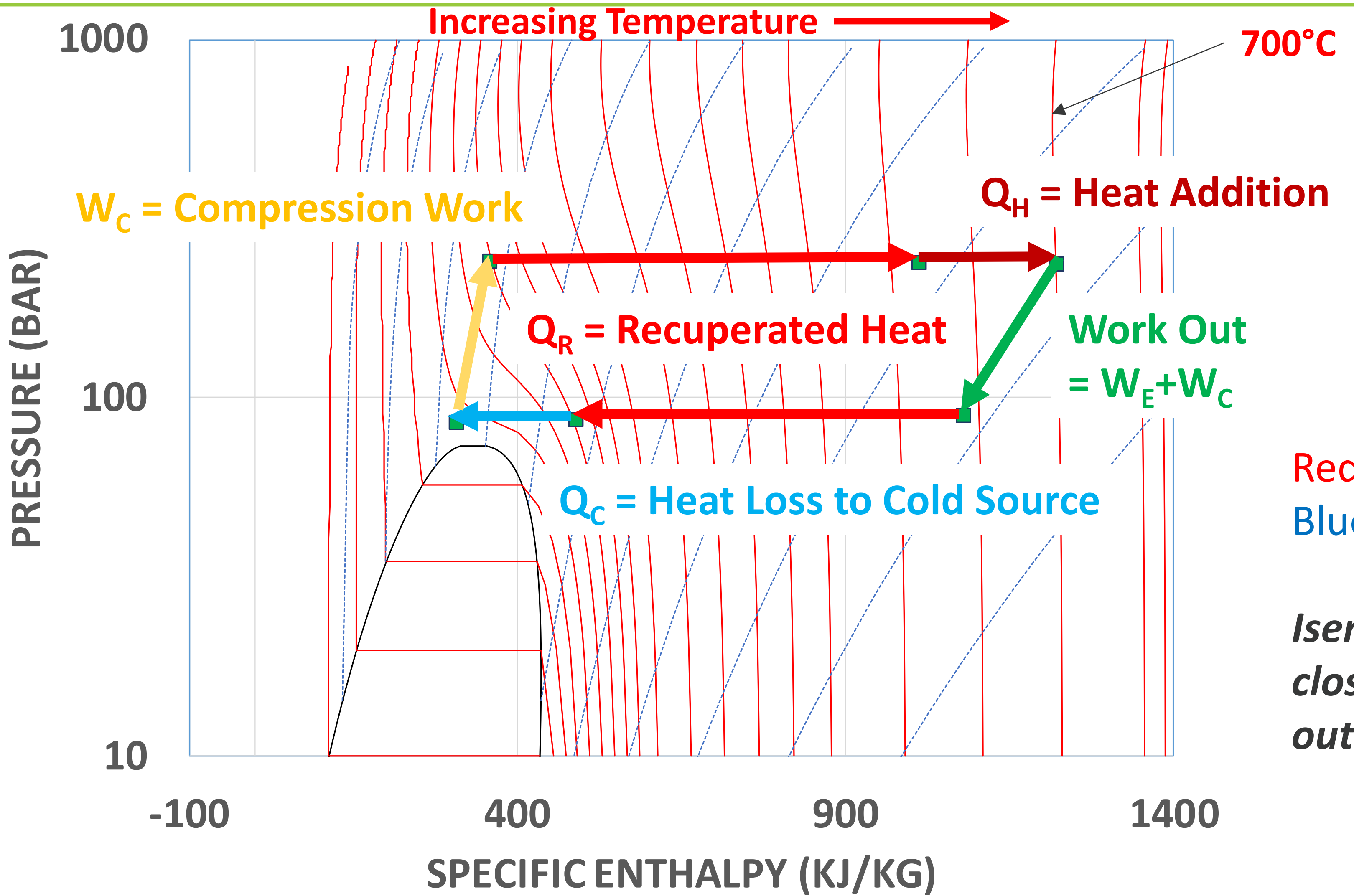
- **Potential for higher efficiency relative to traditional fossil energy cycles**
  - Recuperation of high-quality heat from the turbine exhaust
  - sCO_2 has beneficial thermodynamic properties (high density and specific heat) near the critical point
  - Lower compression work
- **Reduced turbomachinery equipment sizes due to higher working fluid density results in reduced capital costs (moderate impact)**
- **sCO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O**



Source: NETL

Simple Recuperated Cycle

Pressure vs. Specific Enthalpy Diagram



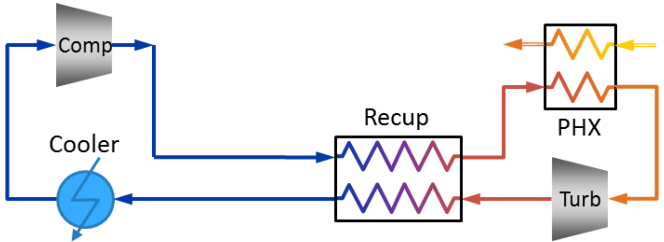
W_C = Compression Work

Q_H = Heat Addition

Q_R = Recuperated Heat

Work Out = W_E+W_C

Q_C = Heat Loss to Cold Source



- Critical Temperature T_c = 31°C
- Critical Pressure P_c = 73.8 bar

Red Lines: Constant Temperature

Blue Lines: Constant Entropy

Isentropic lines are nearly vertical close to the critical point and flatten out with an increase in temperature

sCO$_2$ Power Cycle Technology Program

FY2017 Project Portfolio – Performers and FE Program Funding Sources

ADVANCED COMBUSTION SYSTEMS

Recuperators

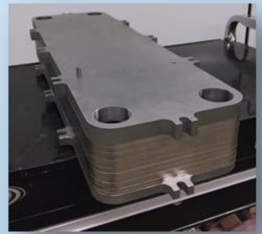
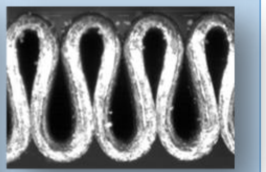
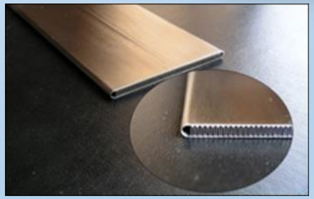
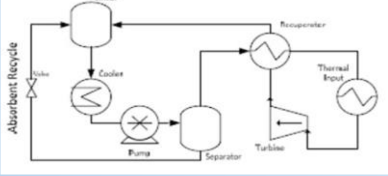
Brayton Energy
Altex Technologies
Oregon State University
Thar Energy

Systems Integration & Optimization

Southwest Research Institute
Electric Power Research Institute

Materials

NETL - RIC

ADVANCED TURBINES

Turbomachinery

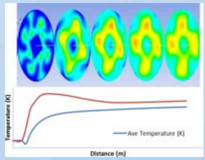
General Electric Company

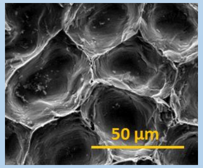
Advanced Concepts for Direct-Fired Cycles

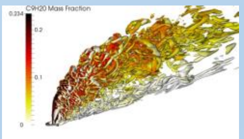
Southwest Research Institute
NETL-RIC
University of Central Florida (UTSR Award)
Georgia Tech (UTSR Award)

Materials

Oak Ridge National Laboratory

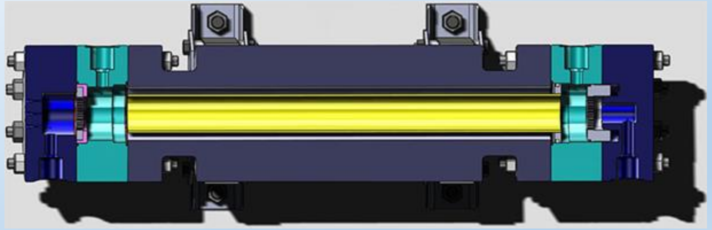







STEP

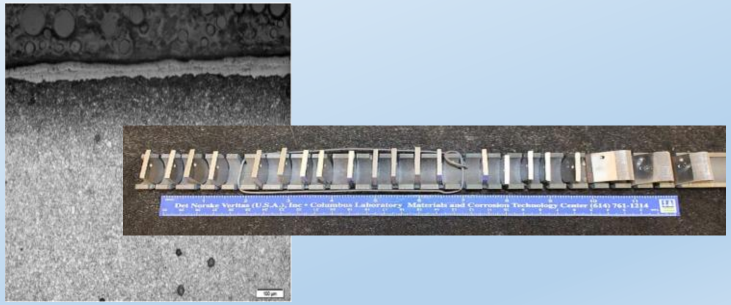
Thar Energy (advanced recuperator)
Gas Technology Institute (10 MW sCO$_2$ pilot plant)



CROSSCUTTING TECHNOLOGY RESEARCH

Materials

Oak Ridge National Laboratory
Electric Power Research Institute



NETL Research & Innovation Center (RIC)

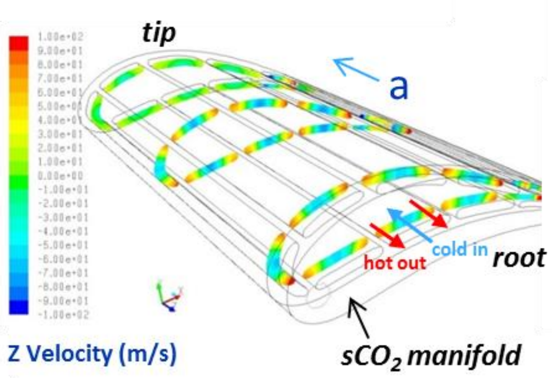
Role in Supercritical CO_2 Power Cycle Technology Program

Goal – Develop technology toward achieving the program goal of increased efficiency using supercritical CO_2-based power cycles.

Approach **–** Perform R&D on turbine blade cooling, oxy-combustion, and materials, along with systems studies.

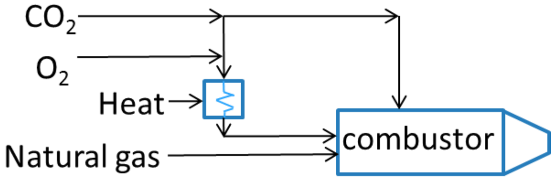
Turbine Blade Cooling

Cool turbine blades to allow higher turbine inlet temperatures.



Oxy-combustion

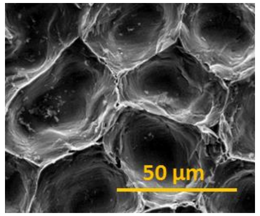
Improve efficiency using higher temperature direct-fired cycle with oxy-combustion.



Proposed Oxy-Fuel Combustor

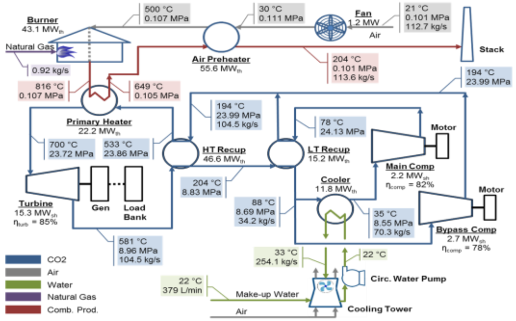
Materials

Evaluate material corrosion, erosion, mechanical property degradation in sCO_2. Identify materials compatible in sCO_2.



Systems Engineering & Analysis

Steady-state and dynamic modeling, techno-economic evaluations of various configurations of sCO_2 power cycle plants (direct- and indirect-fired cycles).



NETL Basis for Cost Estimate of STEP Facility

Source: "10 MW sCO_2 Pilot Plant Techno-economic Analysis – Variations", NETL June 26, 2015

Techno-economic Analysis Results Summary

Comparison of Baseline sCO_2 plant with reheat turbine

- **Tradeoffs that impact result**
  - Reheat brings turbine closer to isothermal expansion, increasing efficiency and lowering COE
  - Reheat turbine and heat exchanger add cost and pressure drop though the reheat exchanger lowering efficiency
- **Key results for reheat turbine**
  - Higher efficiency (1.3-1.5 percentage points)
  - Lower COE (2.2 $/MWh at SC conditions)
  - Higher COE ($0.8/MWh at AUSC conditions)
- **Limits**
  - 2 reheat stages were not economically attractive

Parameter	620 °C TIT		760 °C TIT	
	Baseline	Reheat	Baseline	Reheat
Plant & Cycle Performance				
Coal flow rate (kg/s)	58.46	55.97	51.31	49.64
Gross turb Power (MW)	1,006	980	923	906
sCO_2 cmp Power (MW)	284	265	221	209
Net cycle Power (MW)	711	704	691	687
Auxiliary Power (MW)	161	154	141	137
Tot thermal input (MW)	1,586	1,519	1,392	1,347
Cyc thermal input (MW)	1,462	1,399	1,283	1,241
Plant efficiency (%HHV)	34.7	36.2	39.5	40.8
Cycle efficiency (%)	48.7	50.3	53.9	55.4
Capital Cost and Cost of Electricity				
Total plant cost ($/kW)	3,442	3,419	3,303	3,379
COE w/o T&S ($/MWh)	128.2	126.0	120.0	120.8

Techno-economic Analysis Results Summary

Comparison of Baseline sCO_2 plant with main compressor intercooling

- **Tradeoffs that impact result**
  - Intercooling brings compressor closer to isothermal compression, increasing efficiency and lowering COE
  - Multiple compressor stages and intercoolers add cost and pressure drop though the intercooler lowering efficiency

- **Key results for compressor intercooling**
  - Higher efficiency (0.4-0.6 percentage points)
  - Lower COE (2.2-3.5 $/MWh)

- **Limits**
  - 3 compressor stages with intercooling requires modifying the heat integration scheme due to internal pinch point in flue gas cooler

Parameter	620 °C TIT		760 °C TIT	
	Baseline	Intercool	Baseline	Intercool
Plant & Cycle Performance				
Coal flow rate (kg/s)	58.46	57.39	51.31	50.82
Gross turb Power (MW)	1,006	933	923	869
sCO_2 cmp Power (MW)	284	214	221	169
Net cycle Power (MW)	711	708	691	690
Auxiliary Power (MW)	161	158	141	140
Tot thermal input (MW)	1,586	1,557	1,392	1,379
Cyc thermal input (MW)	1,462	1,460	1,283	1,292
Plant efficiency (%HHV)	34.7	35.3	39.5	39.9
Cycle efficiency (%)	48.7	48.5	53.9	53.4
Capital Cost and Cost of Electricity				
Total plant cost ($/kW)	3,442	3,328	3,303	3,229
COE w/o T&S ($/MWh)	128.2	124.7	120.0	117.8

Techno-economic Analysis Results Summary

Comparison of Baseline sCO_2 plant with reheat turbine & compressor intercooling

- **At SC conditions (620 °C) Reheat & IC sCO_2 plant has:**
  - 2.1 percentage point higher efficiency
  - 3% lower TPC ($/kW)
  - $5.2/MWh lower COE (4% lower)

compared to Baseline sCO_2 plant

- **At AUSC conditions (760 °C) Reheat & IC sCO_2 plant has:**
  - 1.7 percentage point higher efficiency
  - Nearly the same TPC ($/kW)
  - $1.5/MWh lower COE (1% lower)

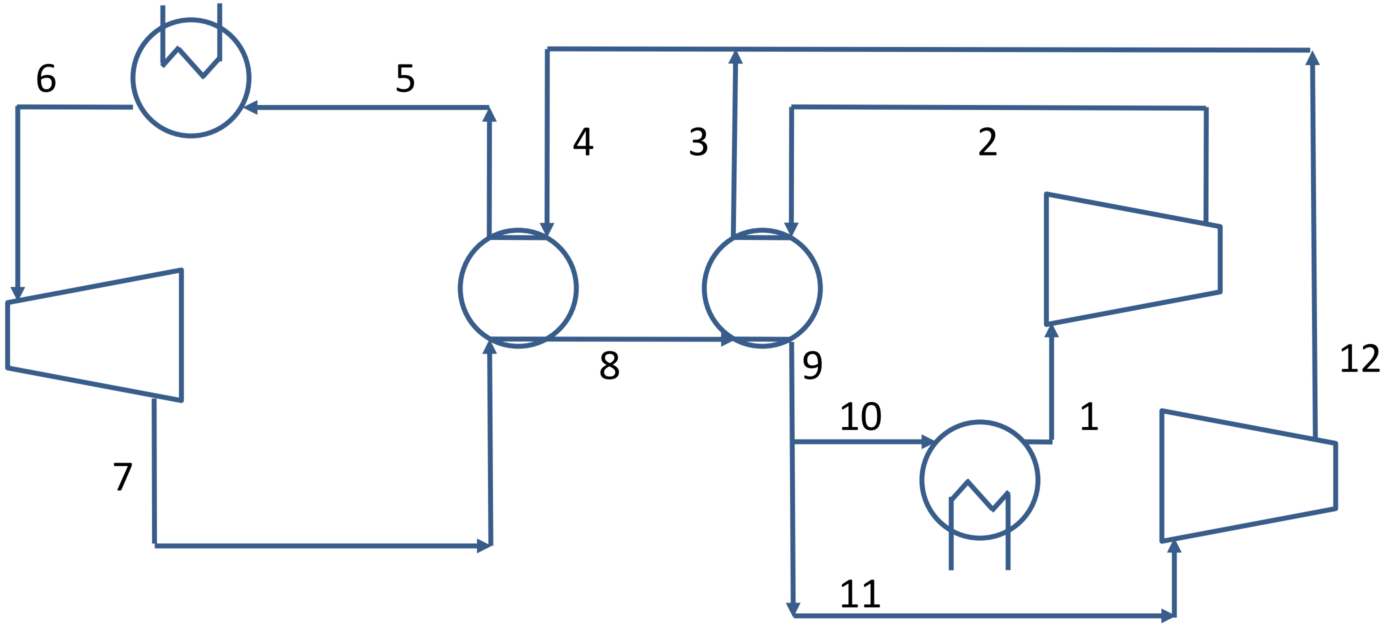
compared to Baseline sCO_2 plant

Parameter	620 °C TIT		760 °C TIT	
	Baseline	Reheat IC	Baseline	Reheat IC
Plant & Cycle Performance				
Coal flow rate (kg/s)	58.46	55.06	51.31	49.24
Gross turb Power (MW)	1,006	913	923	856
sCO_2 cmp Power (MW)	284	200	221	160
Net cycle Power (MW)	711	702	691	685
Auxiliary Power (MW)	161	152	141	135
Tot thermal input (MW)	1,586	1,494	1,392	1,336
Cyc thermal input (MW)	1,462	1,400	1,283	1,252
Plant efficiency (%HHV)	34.7	36.8	39.5	41.2
Cycle efficiency (%)	48.7	50.1	53.9	54.7
Capital Cost and Cost of Electricity				
Total plant cost ($/kW)	3,442	3,324	3,303	3,298
COE w/o T&S ($/MWh)	128.2	123.0	120.0	118.5

Recompression Brayton Cycle

Parameters for Baseline Cycle

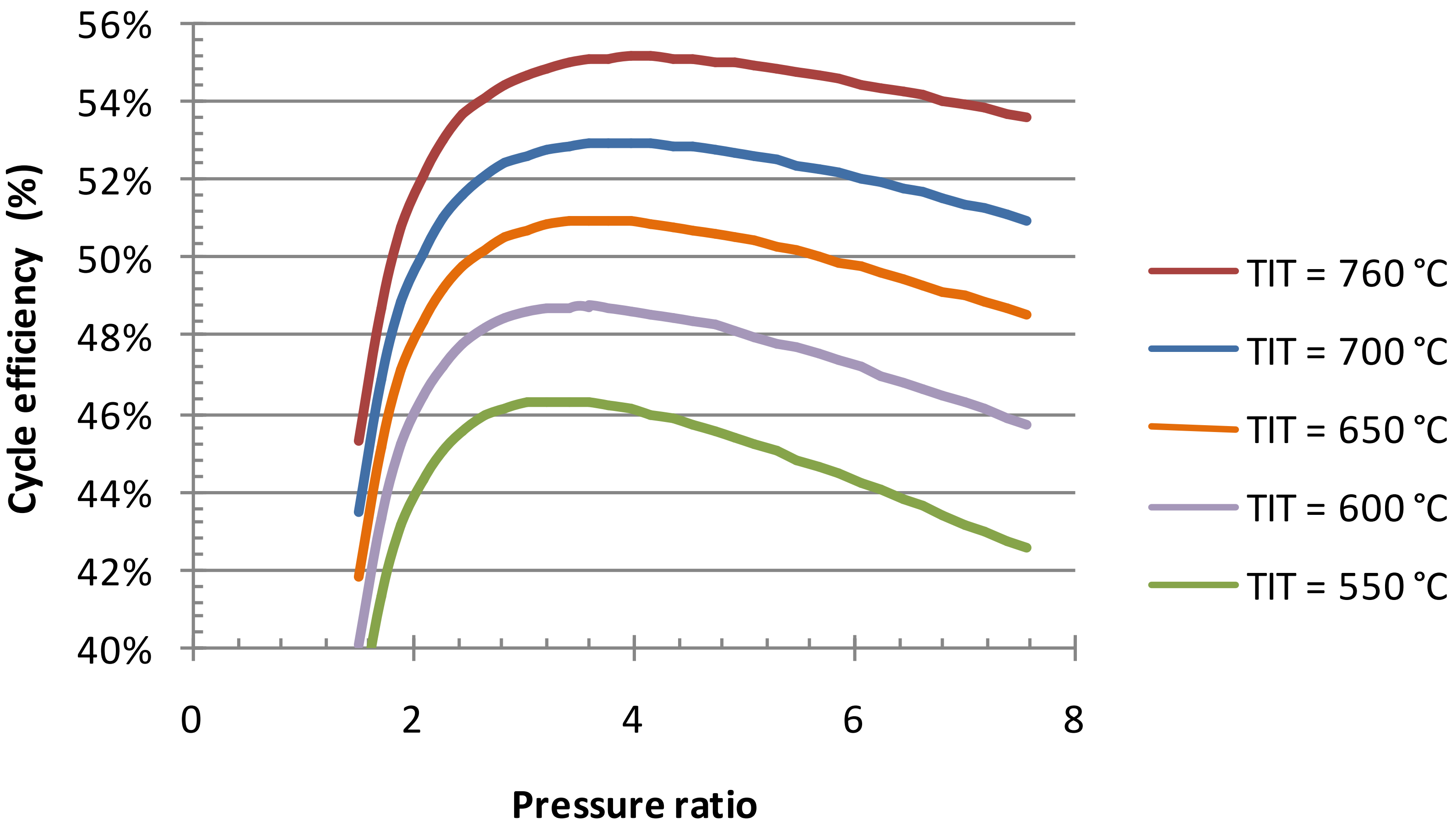
Parameter	Value
Heat source	Generic
Nominal thermal input	64 MMBtu/hr
Turbine exit pressure	1350 psia
CO_2 cooler temperature	35 °C (95 °F)
Turbine isentropic efficiency	0.927
Compressor isentropic efficiency	0.85
Cycle pressure drop	60 psia
Minimum temperature approach	5.6 °C (10 °F)
Turbine inlet temperature	700 °C (1292 °F)
Nominal compressor pressure	5100 psia
Nominal pressure ratio	3.9
Nominal CO_2 cooler bypass fraction	0.283



[1] Shelton, W. and White, Chuck. An Assessment of Supercricitcal CO2 Power Cycles Integrated with Generic Heat Sources. The 4th International Symposium – Supercritical CO2 Power Cycles, September 9-10, 2014, Pittsburgh, Pennsylvania

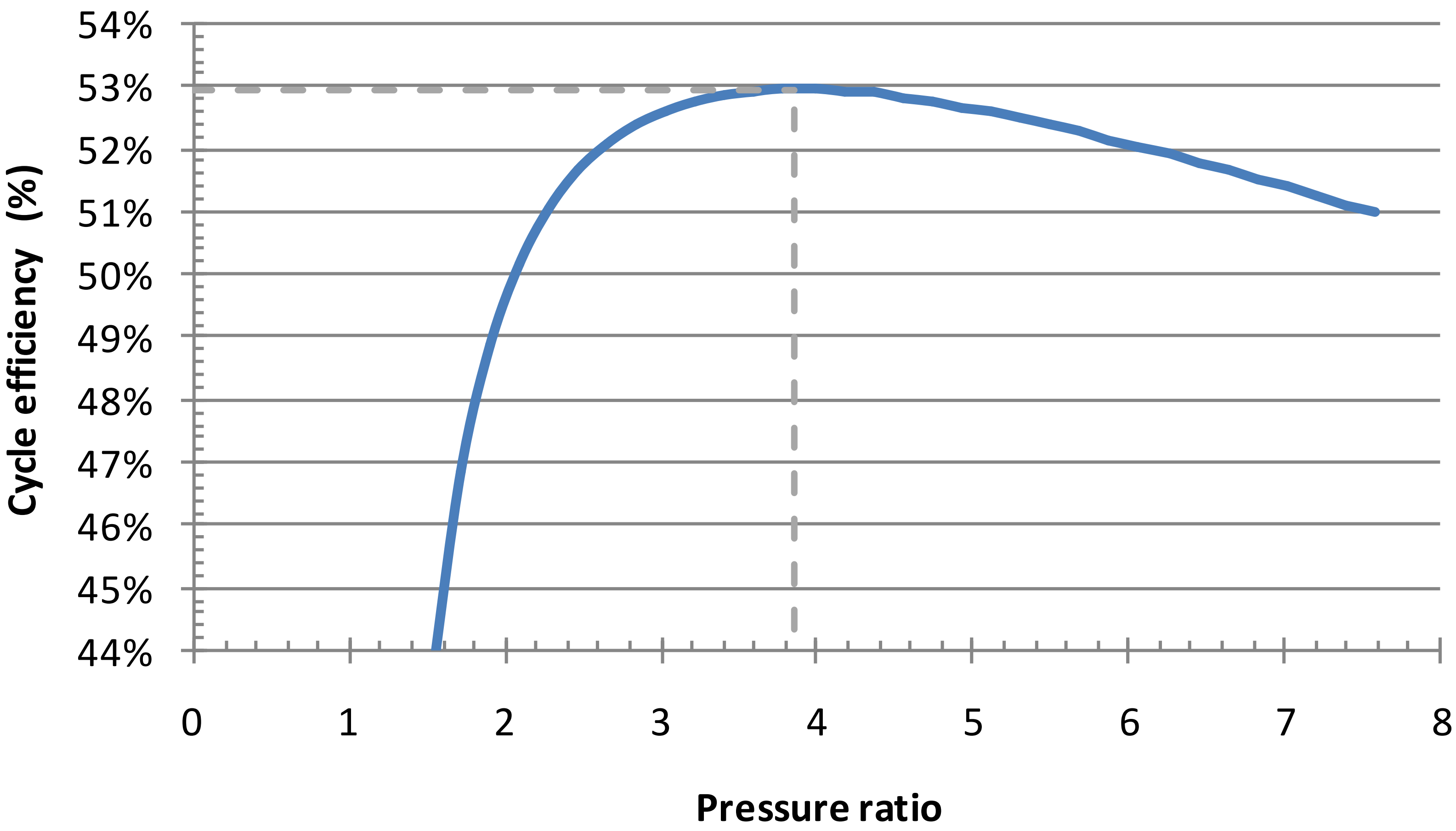
Recompression Brayton Cycle

Sensitivity to turbine inlet temperature



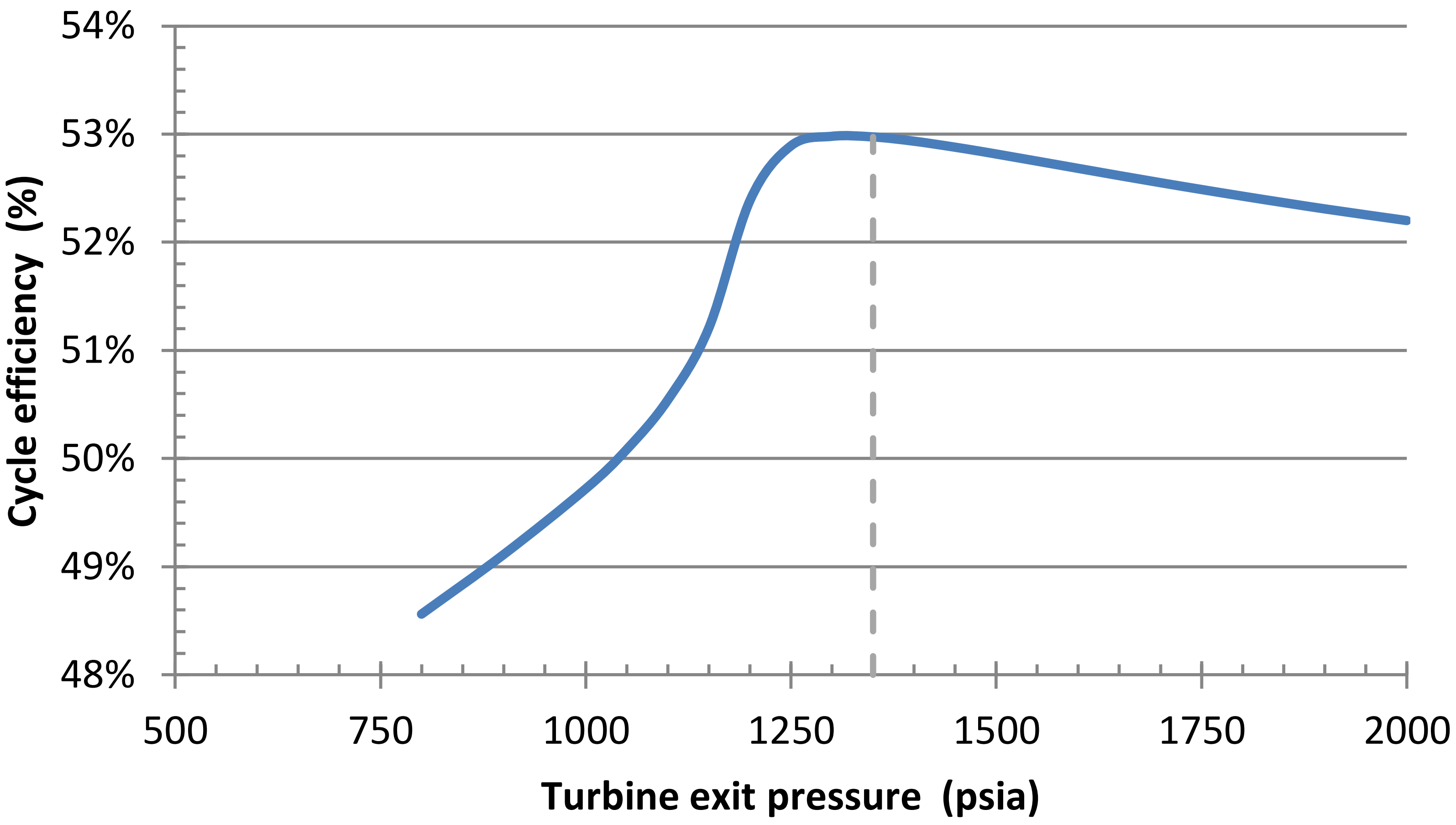
Recompression Brayton Cycle

Sensitivity to pressure ratio



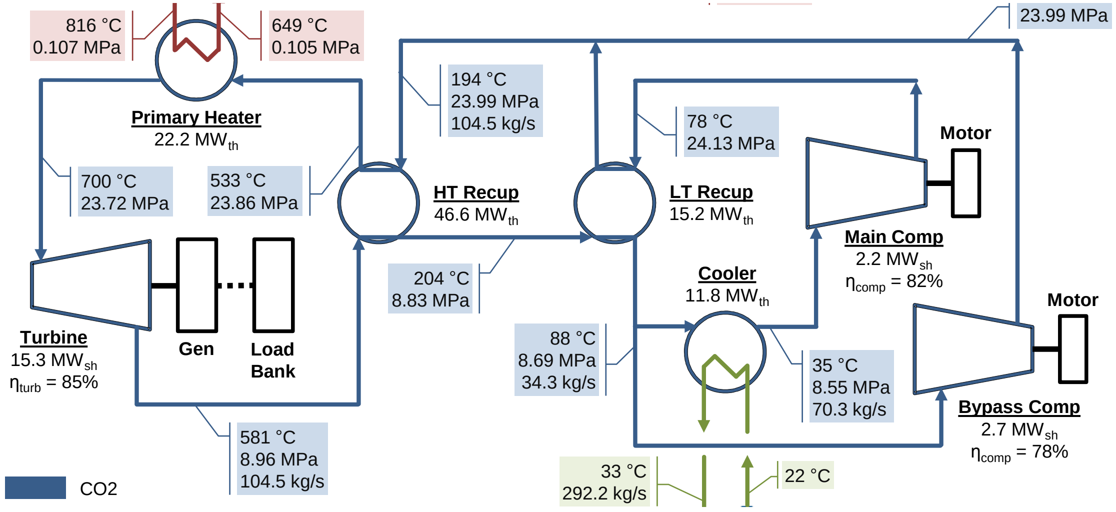
Recompression Brayton Cycle

Sensitivity to turbine exit pressure

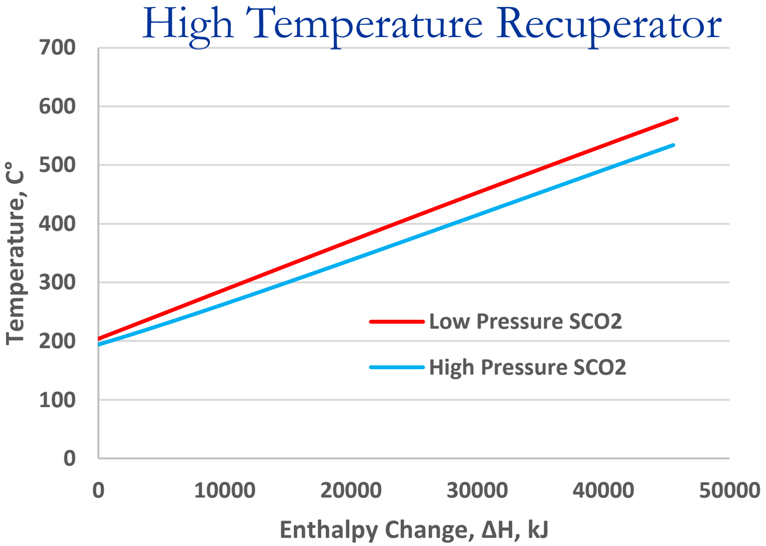


Recompression Closed Brayton Cycle (RCBC)

The slopes of the curves can be matched by differentially controlling the mass flow through the recuperator



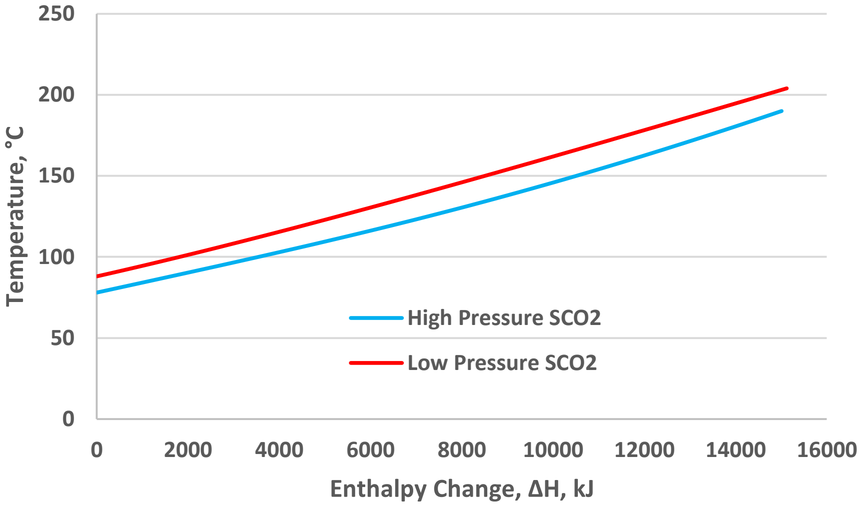
By adding a separate stage of compression, the temperature vs enthalpy curves in the low temperature recuperator can be more closely matched maximizing recuperator effectiveness


High Temperature Recuperator

No Pinch Point

in

Low Temperature Recuperator



Recuperator Parameter Optimization

- Recuperator design requires optimization of pressure drop, heat transfer coefficient, and temperature difference (approach temperature)
- Because levelized cost of electricity (LCOE) is dependent on capital costs as well as efficiency, the most efficient cycle is not necessarily the best option
- Through systems analysis, NETL's Research and Innovation Center determined that reducing recuperator costs by increasing pressure drop and approach temperature to 20 psi and 18°F was worth the penalty in efficiency for a 10 MWe Recompression Closed Brayton Cycle

- **Reality Check: A 550 MWe RCBC would require approximately 4000 MWt of recuperative heat duty…**

  …that is a lot of material

NETL – Materials Research for sCO_2 Cycles

Goal – to enable the sCO_2 Power Cycle technologies

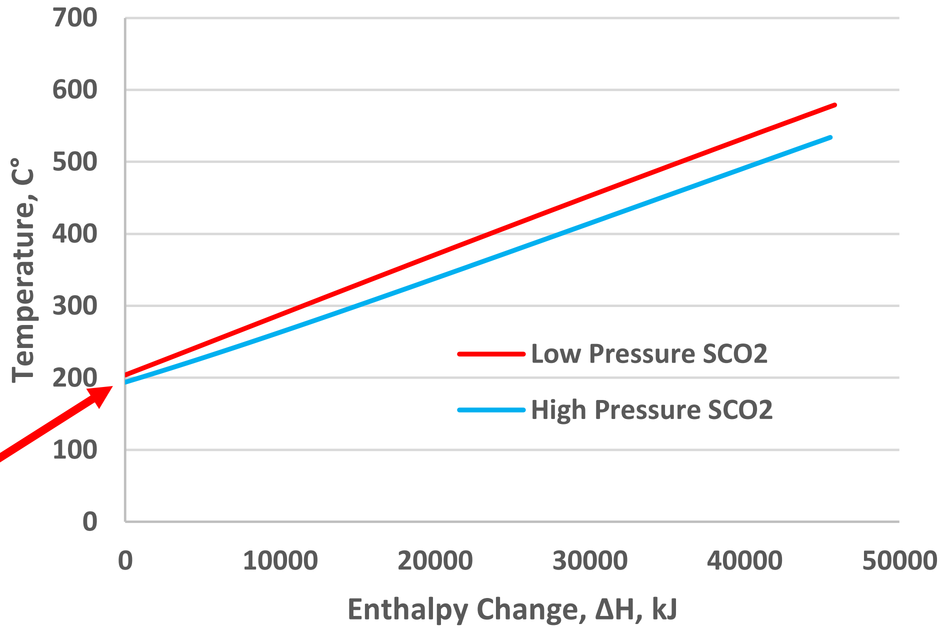
- **Corrosion of advanced alloys in direct sCO_2 power cycle environment**
  - High-temperature oxidation
  - Low-temperature corrosion
- **High-temperature oxidation of advanced alloys in indirect sCO_2 power cycles**
- **Mechanical property – environment interactions**
  - Effect of sCO_2 on fatigue crack growth
- **Materials issues in manufacturing compact heat exchangers**
  - Diffusion bonding (DB)
  - Transient liquid phase bonding (TLPB)
- **High-temperature corrosion of bonds in sCO_2**

Recuperator Pinch Point

The temperature increase with enthalpy is dependent on the specific heat of the fluid (Cp)

$$\Delta T = \Delta H / Cp$$

If Cp increases with pressure; therefore, the temperature change of the low pressure hot side will be higher than the temperature change of the high pressure cold side (i.e. the slopes of the curves are different)



Pinch Point

The pinch point limits the heat exchanger effectiveness

sCO_2 and IGCC Performance Comparison

All cases use same coal and gasifier, w/CCS

- **sCO_2 plants achieve greater efficiency due to *cycle* efficiency differences**
  - Generate 13-22% more net power on 6% percent less coal, but ~2.5x more oxygen needed
- **Case 2 has 2.9 percentage point higher efficiency compared to Baseline sCO_2 plant**
  - Generates 8% more net power using the same coal feed and 3% more aux power
- **All plants require about 26% of gross power output for auxiliaries**
- **sCO_2 plants capture more carbon**
  - IGCC capture limited by water-gas shift reaction and Selexol process
  - Case 2 eliminates syngas fuel in coal dryer

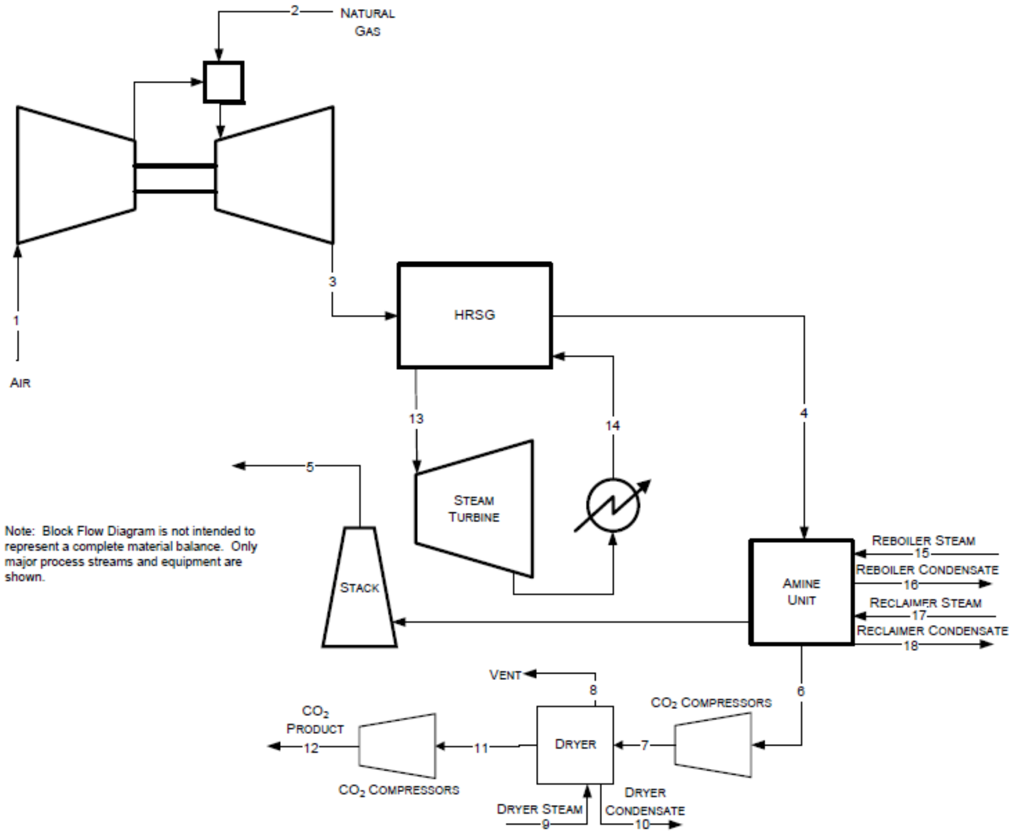
Parameter	IGCC [5]	sCO_2 Baseline	sCO_2 Case 2
Coal flow rate (kg/hr)	211,040	198,059	198,059
Oxygen flow rate (kg/hr)	160,514	391,227	394,234
sCO_2 flow rate (kg/hr)	---	7,243,859	7,734,832
Carbon capture fraction (%)	**90.1**	**97.6**	**99.4**
Captured CO_2 purity (mol% CO_2)	99.99	99.80	99.80
Net plant efficiency (HHV %)	**31.2**	**37.7**	**40.6**
sCO_2 power cycle efficiency (%)	---	61.7	61.9
F-frame gas turb. efficiency (HHV %)	35.9	---	---
Steam power cycle efficiency (%)	39.0	---	---
Raw water withdrawal (m^3/s)	0.355	0.340	0.337
Power summary (MW)			
Coal thermal input (HHV)	1,591	1,493	1,493
Steam turbine power output	209	0	0
Gas turbine power output	464	0	0
sCO_2 turbine power output	0	777	828
Gross power output	673	777	828
Total auxiliary power load	177	215	222
Net power output	**497**	**562**	**606**

Source: Weiland, Nand White, C., "Techno-economic Analysis of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle," 8th International Conference on Clean Coal Technologies, May 8-12, 2017.

NGCC with Post Combustion CO_2 Capture

Incumbent to Beat for Direct NG fueled sCO_2 Power Cycles

	NGCC Baseline Cases		
	F-Class Turbine		H-Frame Turbine
Case	B31A[1]	B31B[1]	2b[2]
Net power output (MWe)	630	559	721
Carbon capture %	0	90	Yes
Steam cycle	2400 psig/1050°F/ 1050°F		2400 psig/1075°F/ 1075°F
Net Plant Efficiency (HHV) %	51.5	45.7	47.2
COE ($/MWh) excluding CO2 T&S	57.6	83.3	76.5
COE ($/MWh) including CO2 T&S		87.3	78.4



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Source: NETL

- **Analysis underway for sCO_2 direct-fired plant with natural gas feed**

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[1] National Energy Technology Laboratory (NETL). (2015, July 6). Cost and Performance Baseline for Fossil Energy Plants, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3. DOE/NETL-2015/1723, Pittsburgh, Pennsylvania

[2] National Energy Technology Laboratory (NETL). (2012, June 25). Post Combustion Carbon Capture Approaches for Natural Gas Combined Cycle (NGCC) Power Plants. DOE/NETL-341/061812. Pittsburgh, Pennsylvania

Sensitivity Analysis Results Summary

sCO$_2$ power cycle component TPC, COE versus ΔTPC

- **Bar chart inserts denote sCO$_2$ cycle component cost**
- **Solid blue lines denote sCO$_2$ case COE versus ΔTPC**
- **Horizontal dashed lines denote Rankine case COE**
- **Vertical solid lines (red markers) denote sCO$_2$ case COE**
- **Vertical dashed lines denote ΔTPC where sCO$_2$ case COE equals Reference COE**