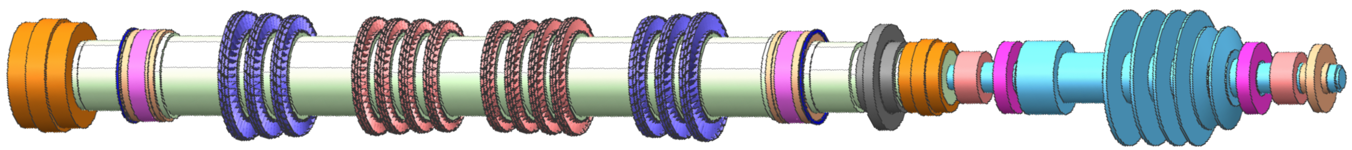
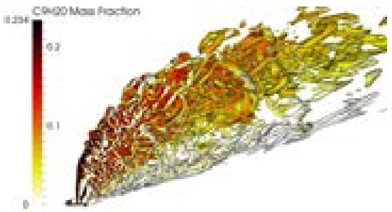
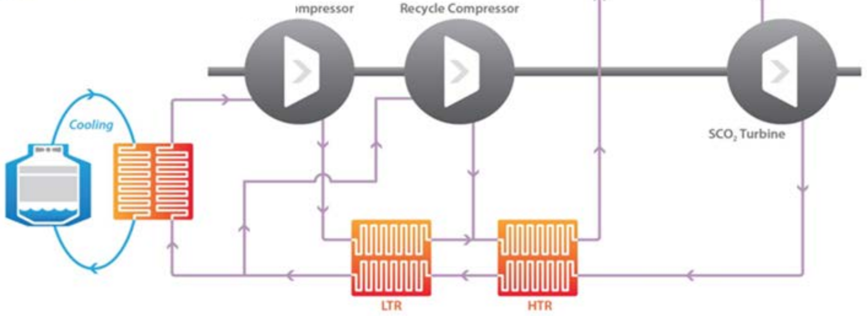
Overview of Supercritical Carbon Dioxide Based Power Cycles for Stationary Power Generation

Presented to: ARPA-E Workshop on High Efficiency High Temp. Modular Power Utilizing Innovative Designs, Materials, and Manufacturing Techniques

October 19 - 20, 2017







Solutions for Today | Options for Tomorrow

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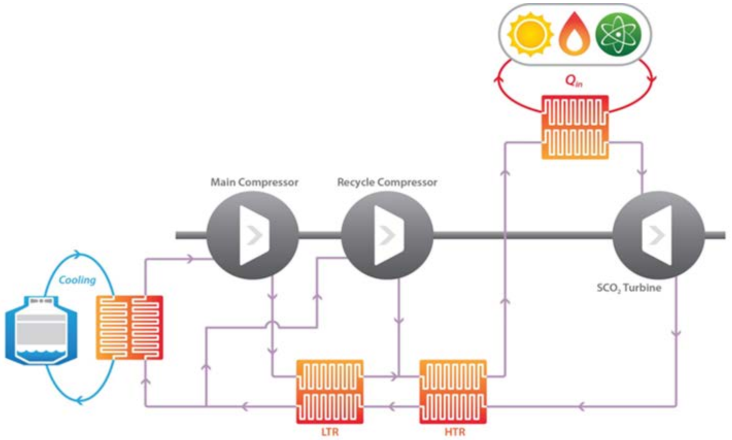
US DOE Office of Fossil Energy
NETL

U.S. DEPARTMENT OF ENERGY

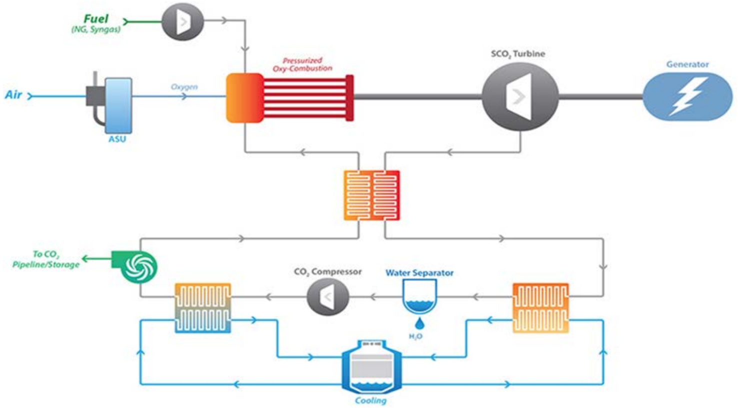
Presentation Outline

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 of interested to FE
- FE System Studies with sCO_2 Power Cycles
  - Cost and performance
- Technology Challenges
- Key Projects
- Summary and Conclusions



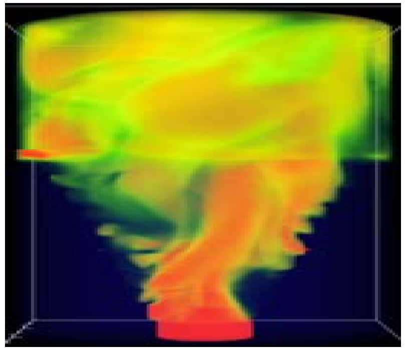
Indirectly-heated cycle



Directly-heated cycle

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

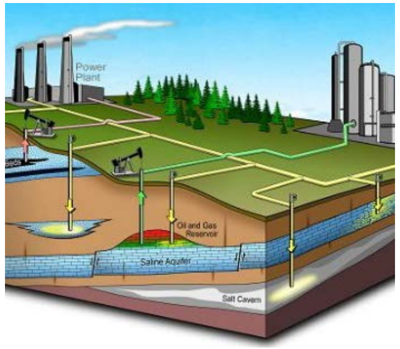


Computational Science & Engineering

- 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

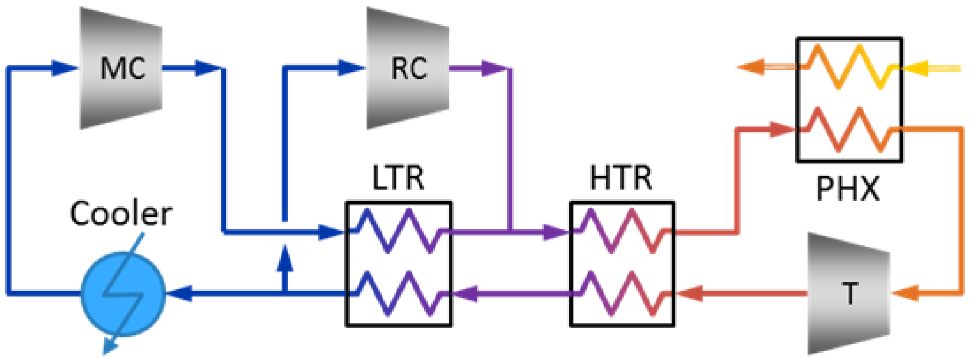
- Technical Project Management
- Market & Regulatory Analysis

FE Base Program in sCO_2 Power Cycles

Two related cycles for advanced combustion and gasification applications

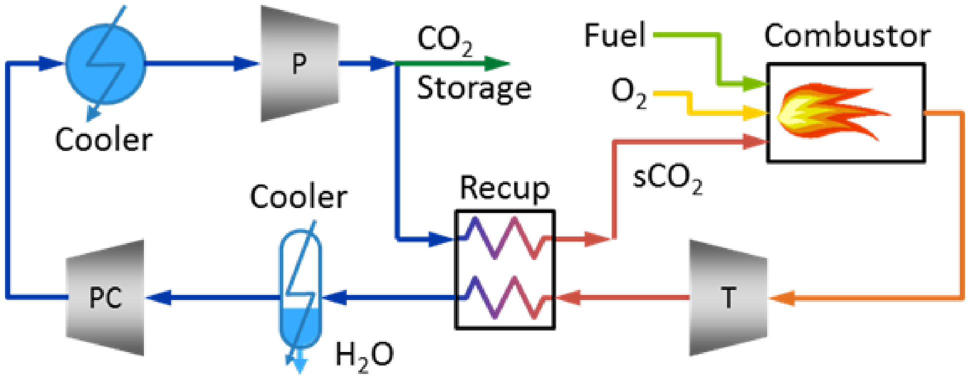
Indirectly-heated cycle (RCB cycle)

- 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



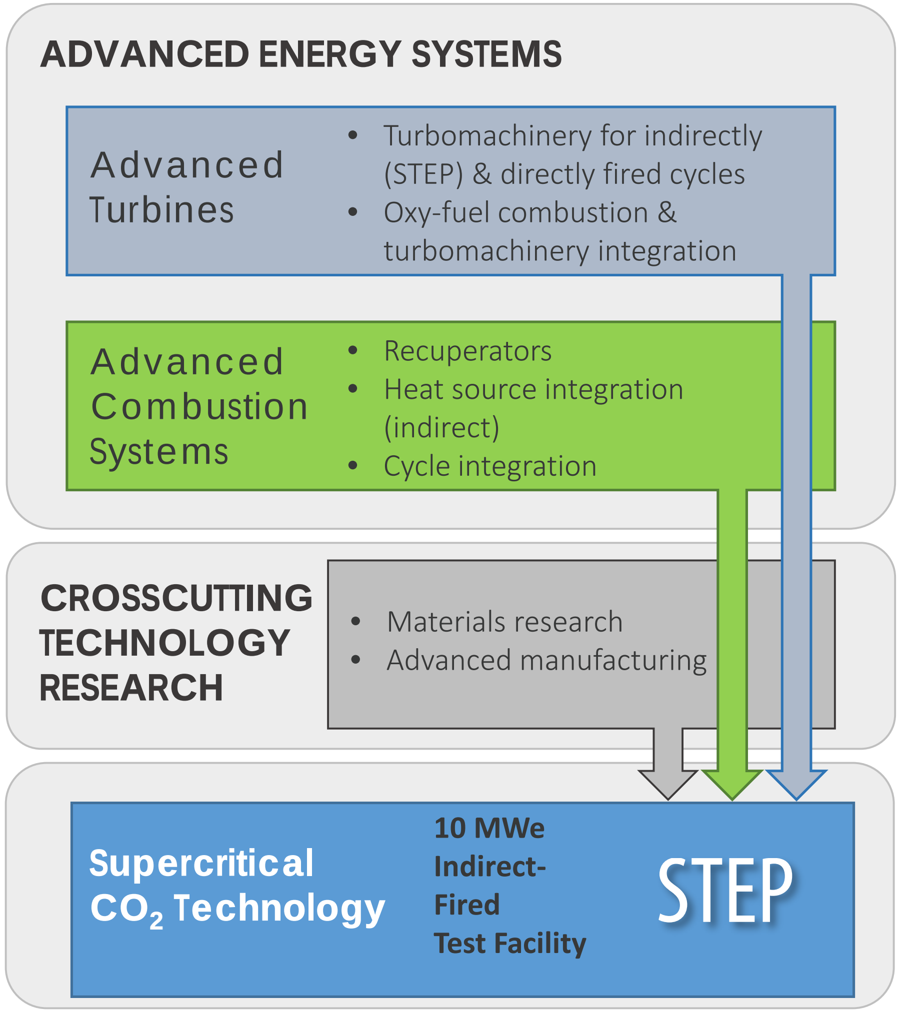
Directly-heated cycle (Allam cycle)

- 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



- **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

Why supercritical CO_2 (sCO_2)?

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

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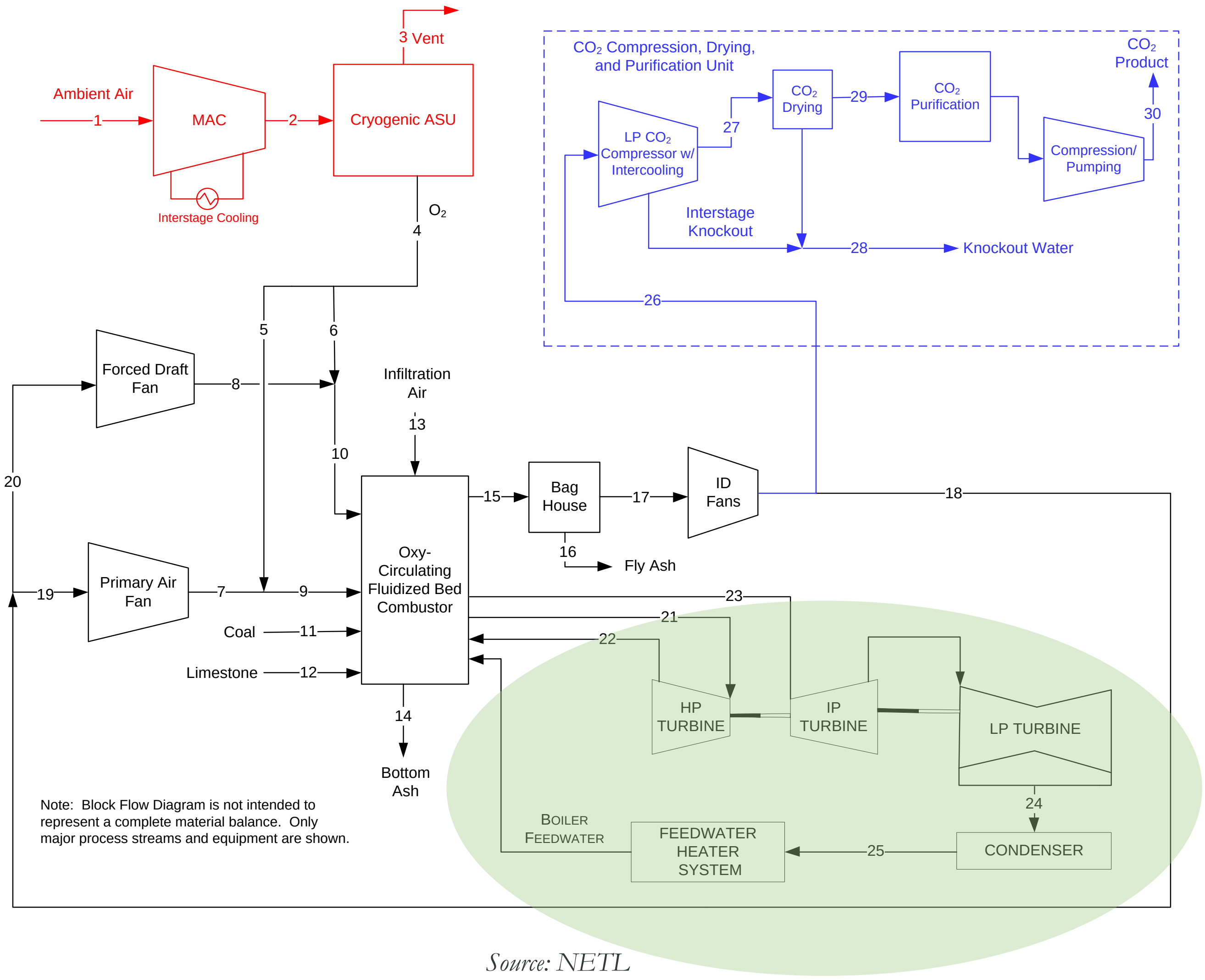
- **Moderate conditions for supercritical state**
  - CO_2 Critical Point
    - Temperature: 31.06 C , (87.9 ºF)
    - Pressure: 7.4 MPa , (1071.8 psia)
  - Approximately 50% increase in specific heat (Cp) around critical point at likely cycle conditions
- **Excellent fluid properties**
  - Liquid-like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

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

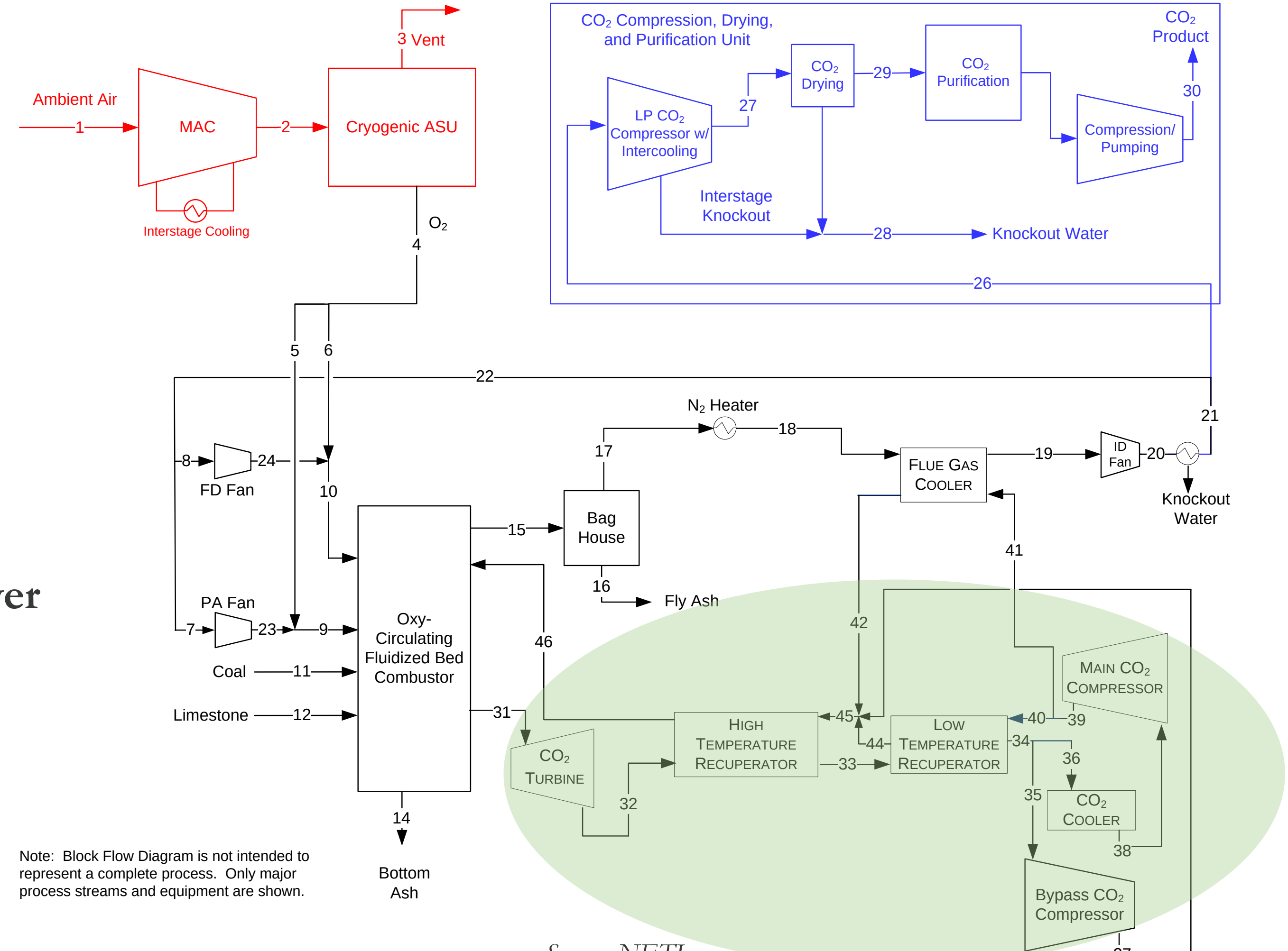


Source: NETL

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

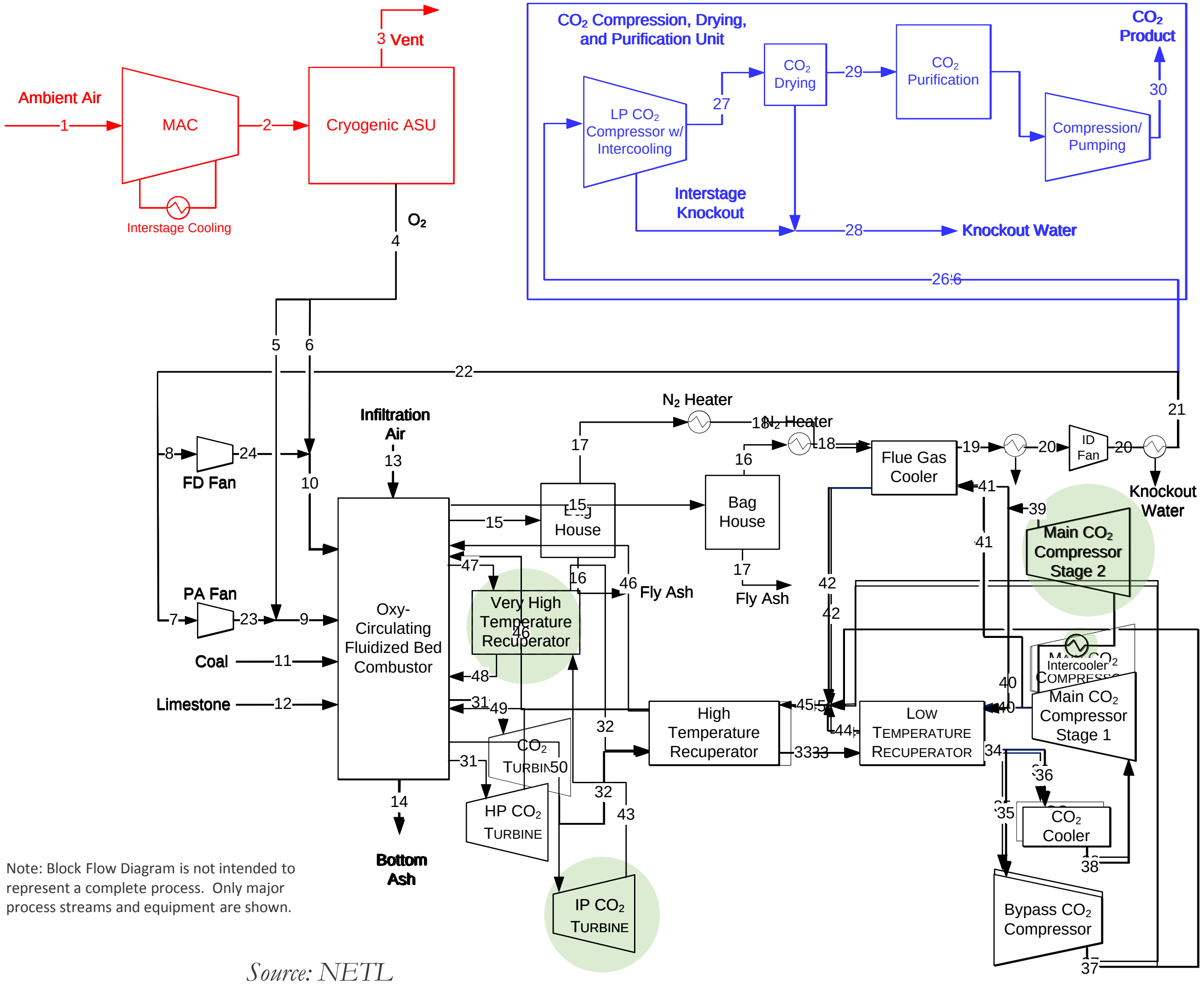


Source: NETL

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

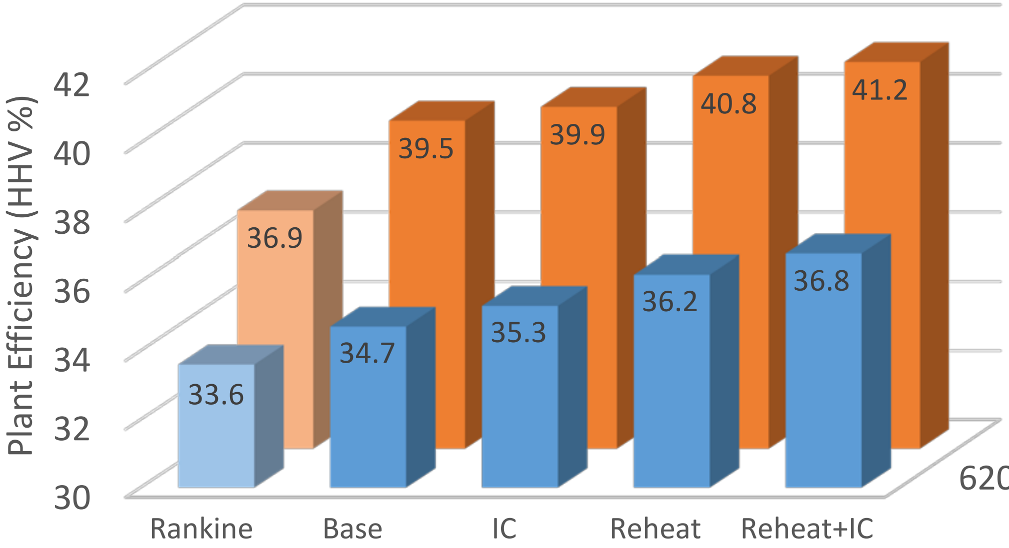


Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

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



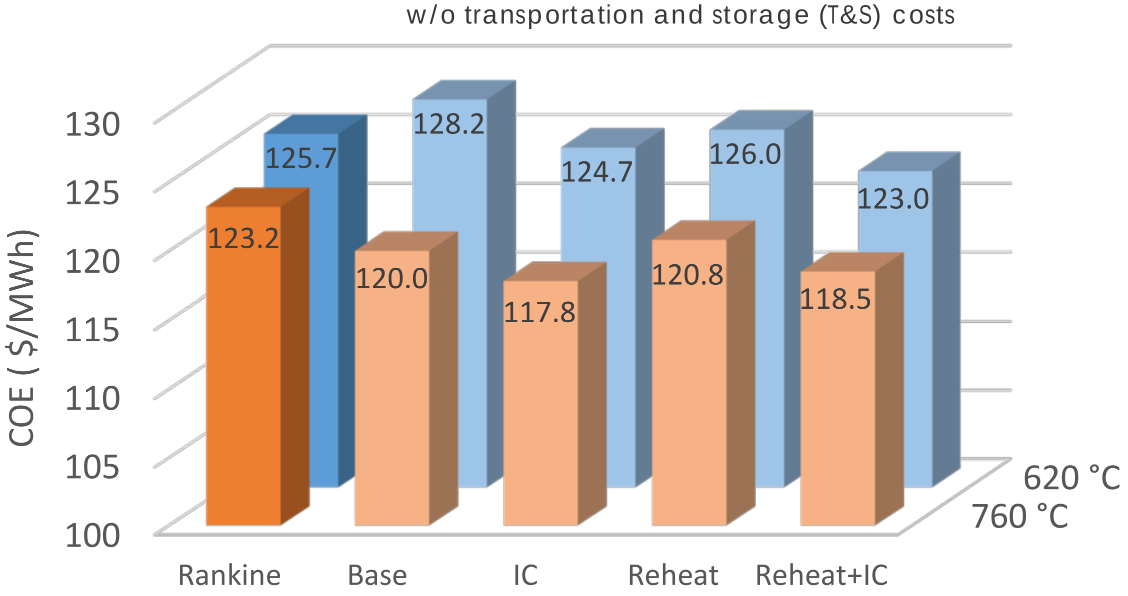
Source: NETL

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

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**



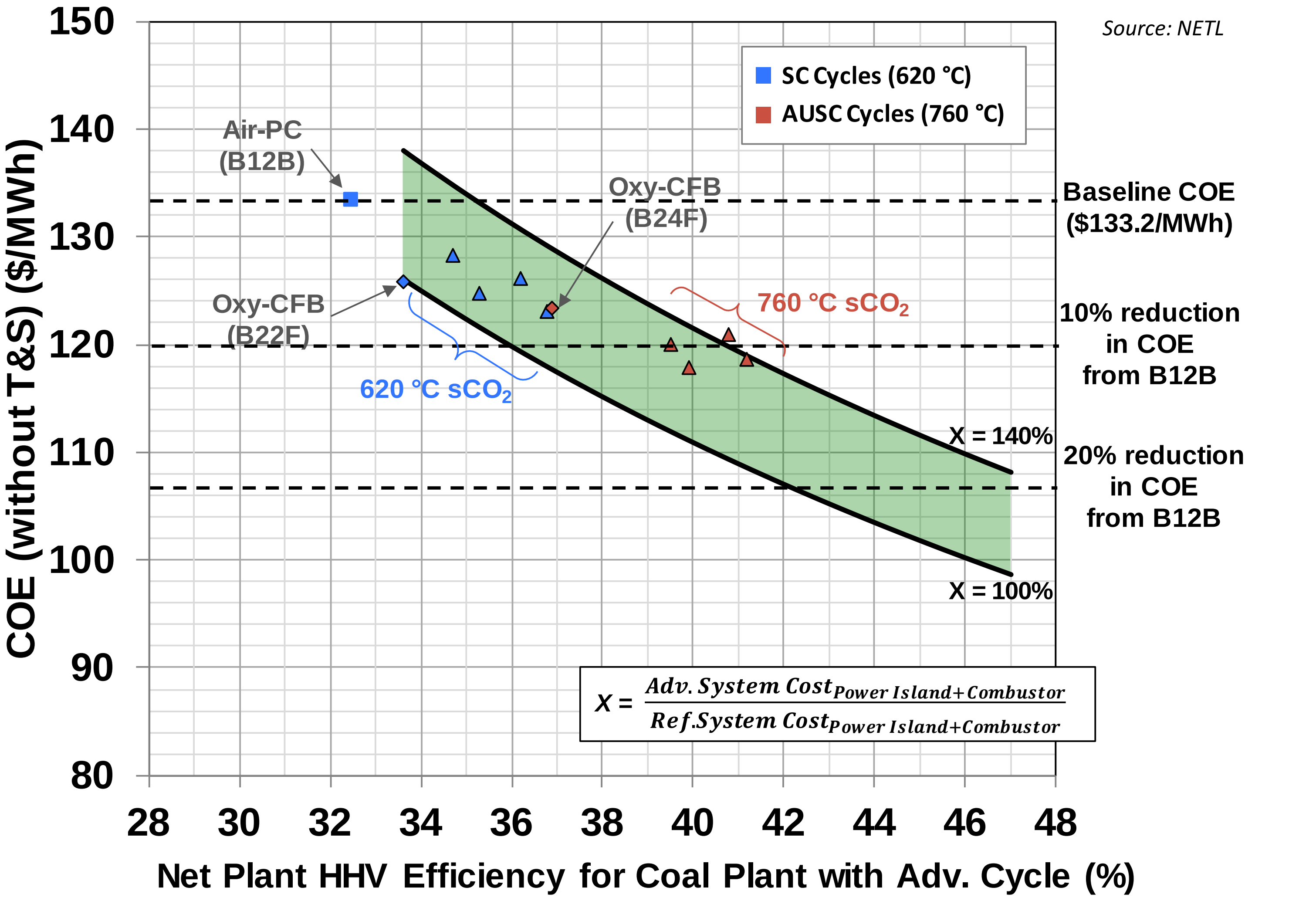
Source: NETL

- **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

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**



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.

Gasification Based Direct SCO2 Power Cycle

Preliminary Performance Comparison

- **sCO_2 plant achieves greater efficiency, 37.7% vs. 31.2%, due to *cycle* efficiency differences**
  - Generates 13% more net power
  - Requires 6% percent less coal
- **sCO_2 plant achieves greater carbon capture fraction**
  - IGCC capture limited by water-gas shift reaction and Selexol process
- **Similar results obtained in 2014 EPRI study[2]**
  - sCO_2 net HHV plant efficiency of 39.6% with 99.2% CO_2 capture at 98.1% purity

Parameter	IGCC	sCO_2 Cycle	EPRI sCO_2 Cycle[2]
Net power output (MWe)	497	562	583
Net plant efficiency (HHV %)	31.2	37.7	39.6
COE (w/o T&S) (2011$/MWh)	152.6	136.4	127.7
Carbon capture fraction (%)	90	98	99

Parameter	IGCC[5]	sCO_2 Cycle
Coal flow rate (kg/hr)	211,040	198,059
Oxygen flow rate (kg/hr)	160,514	391,227
sCO_2 flow rate (kg/hr)	---	7,243,859
Carbon capture fraction (%)	90.1	97.6
Captured CO_2 purity (mol% CO_2)	99.99	99.80
Net plant efficiency (HHV %)	31.2	37.7
sCO_2 power cycle efficiency (%)	---	55.4
F-frame gas turbine efficiency (HHV %)	35.9	---
Steam power cycle efficiency (%)	39.0	---
Raw water withdrawal (m^3/s)	0.355	0.340
Carbon conversion (%)	99.5	99.5
Power summary (MW)		
Coal thermal input (HHV)	1,591	1,493
Steam turbine power output	209	0
Gas turbine power output	464	0
sCO_2 turbine power output	0	777
Gross power output	673	777
Total auxiliary power load	177	215
Net power output	497	562

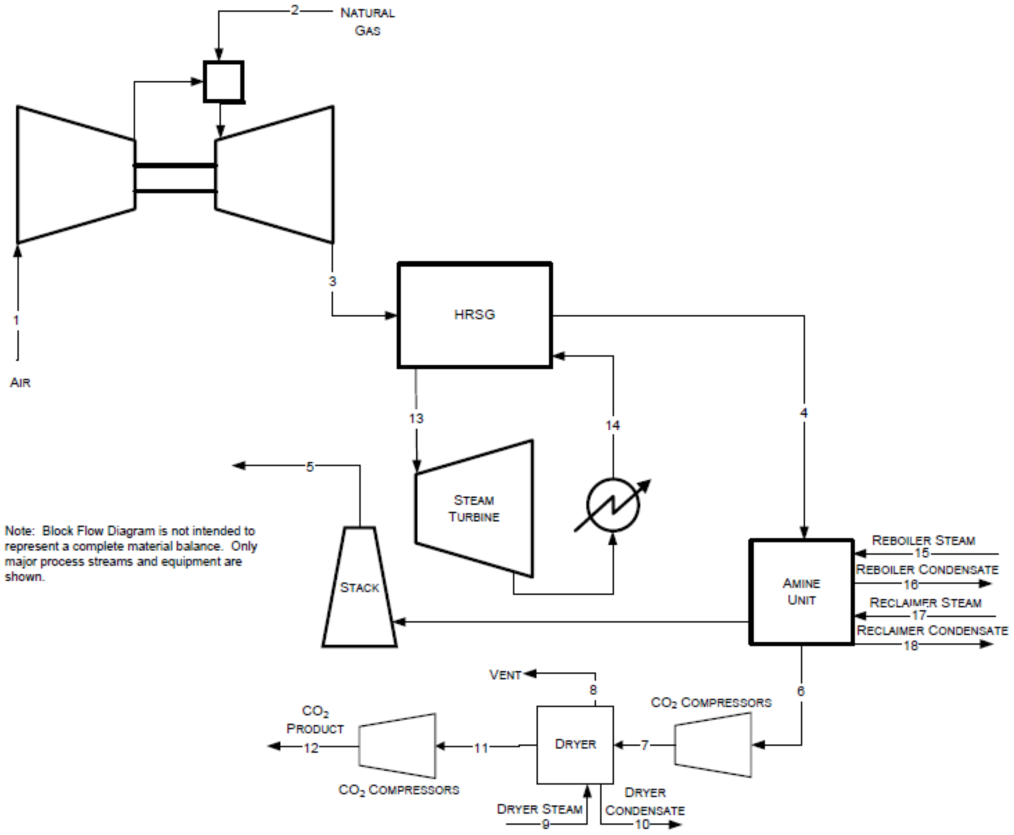
[2] Electric Power Research Institute (EPRI). (2014, December). Performance and Economic Evaluation of Supercritical CO2 Power Cycle Coal Gasification Plant (3002003734). Palo Alto, California.
[5] National Energy Technology Laboratory (NETL). (2015, July 31). Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2b – Year Dollar Update. DOE/NETL-2015/1727, Pittsburgh, Pennsylvania.

Source: Weiland, N., Shelton, W., and White, C., "Performance of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle," First Workshop on High Efficiency, Low Emissions Coal-Fired Plant (HELE2016), Tokyo, Japan, May 23, 2016.

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



Source: NETL

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

[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

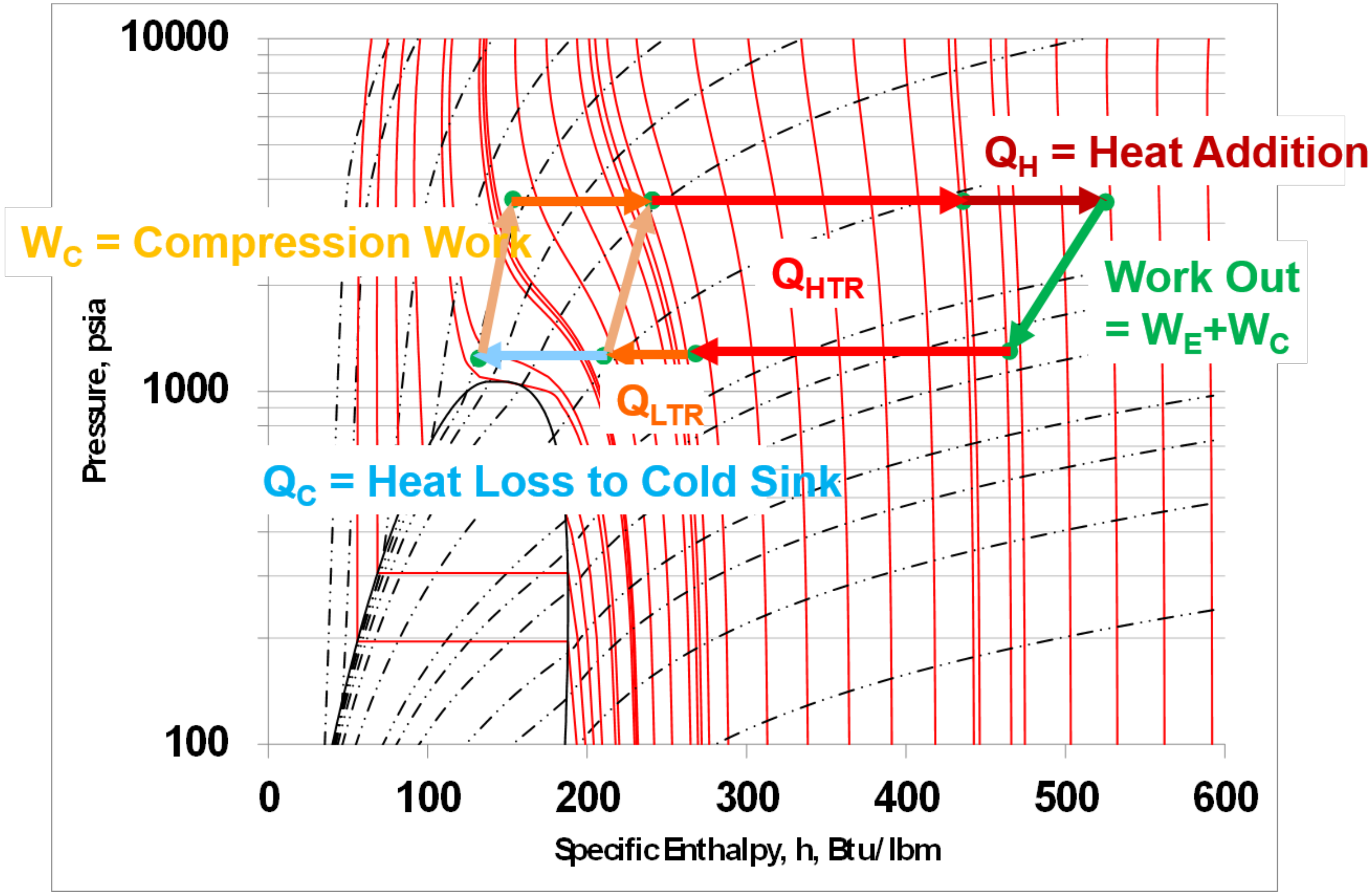
Technical Challenges for SCO2 Power Cycles

For fossil energy applications – Recompression Brayton cycles

- **Need to demonstrate cycle efficiencies greater than 50%**
  - Expanders ≥ 92 %
  - Compressors ≥ 85
- **Material performance and cost**
- **Balanced recuperator performance**
  - effectives, pressure drop, approach temperature and cost
- **Primary heat soruce and cycle integration**
  - Low temperature heat addition
  - Energy flux
  - Pressure drop

Recompression Closed Brayton Cycle

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



Pressure vs. Specific Enthalpy Diagram

Material Limits

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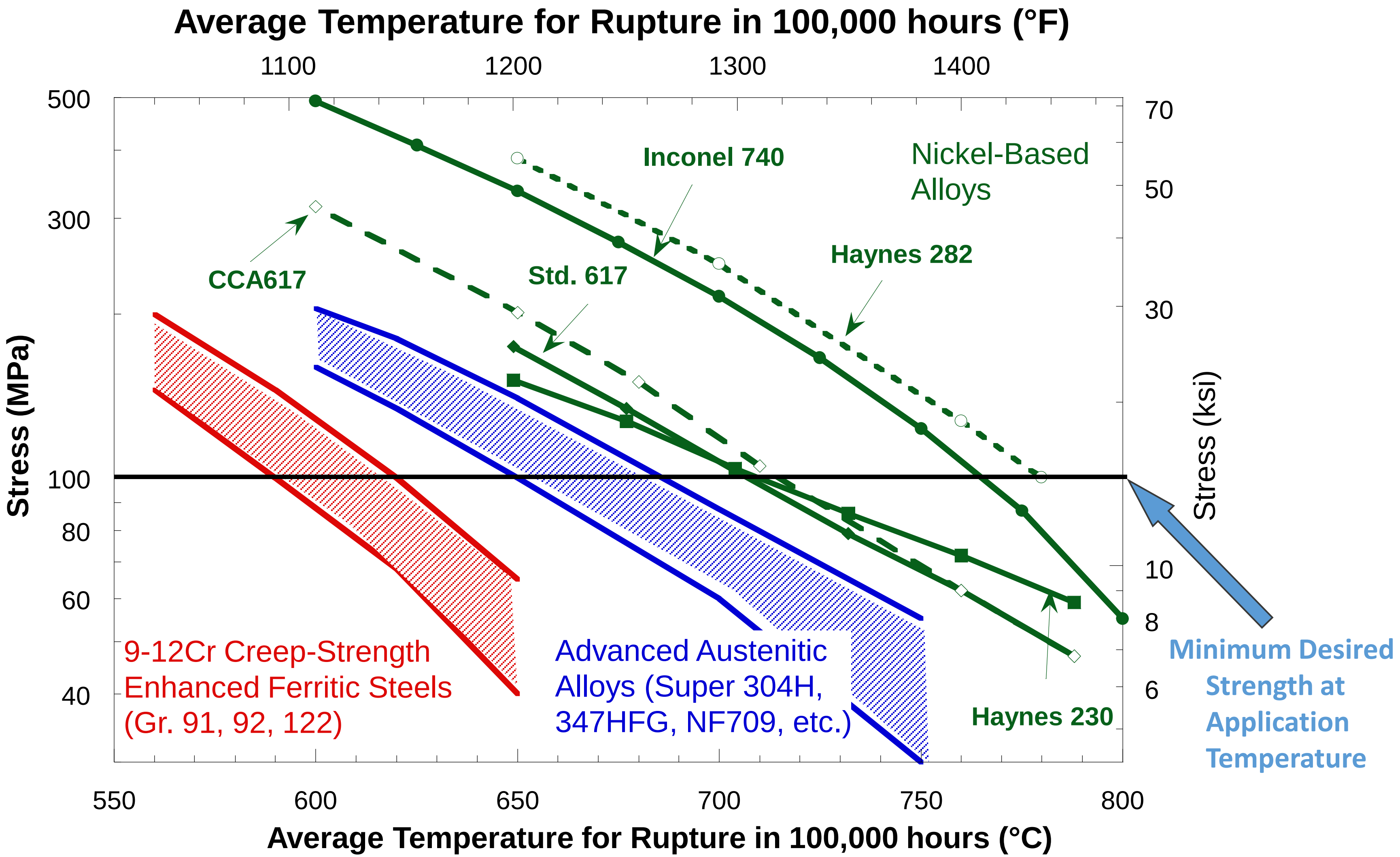


Source: EPRI, Project FE0025064 "Materials for Advanced Ultra-supercritical Steam Turbines – Advanced Ultra-supercritical Component Demonstration" NETL 2017 Crosscutting Research Project Review Meeting, March 23, 2017, Pittsburgh, PA.

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

sCO_2 Power Cycle Technology Program

FY2017 FE Project Portfolio – Performers and FE Program Funding Sources

ADVANCED COMBUSTION SYSTEMS

Recuperators

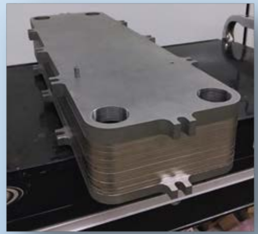
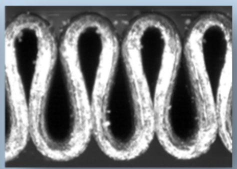
Brayton Energy
Altex Technologies
Oregon State University
Thar Energy

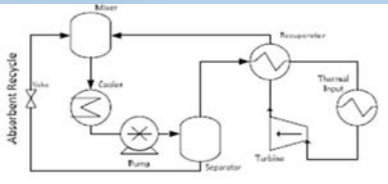
Systems Integration & Optimization

Southwest Research Institute
Electric Power Research Institute

Materials

NETL - RIC



ADVANCED TURBINES

Turbomachinery

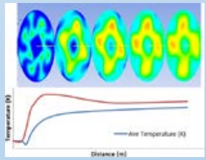
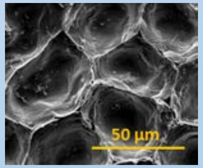
General Electric Company

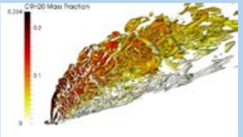
Advanced Concepts for Direct-Fired Cycles

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

Materials

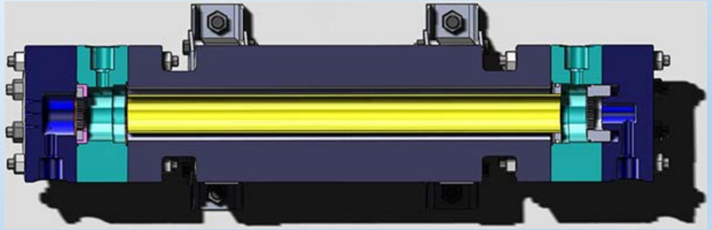
Oak Ridge National Laboratory



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


Supercritical Carbon Dioxide 10 MWe Pilot Plant Test Facility

Gas Technology Institute

NATIONAL ENERGY TECHNOLOGY LABORATORY

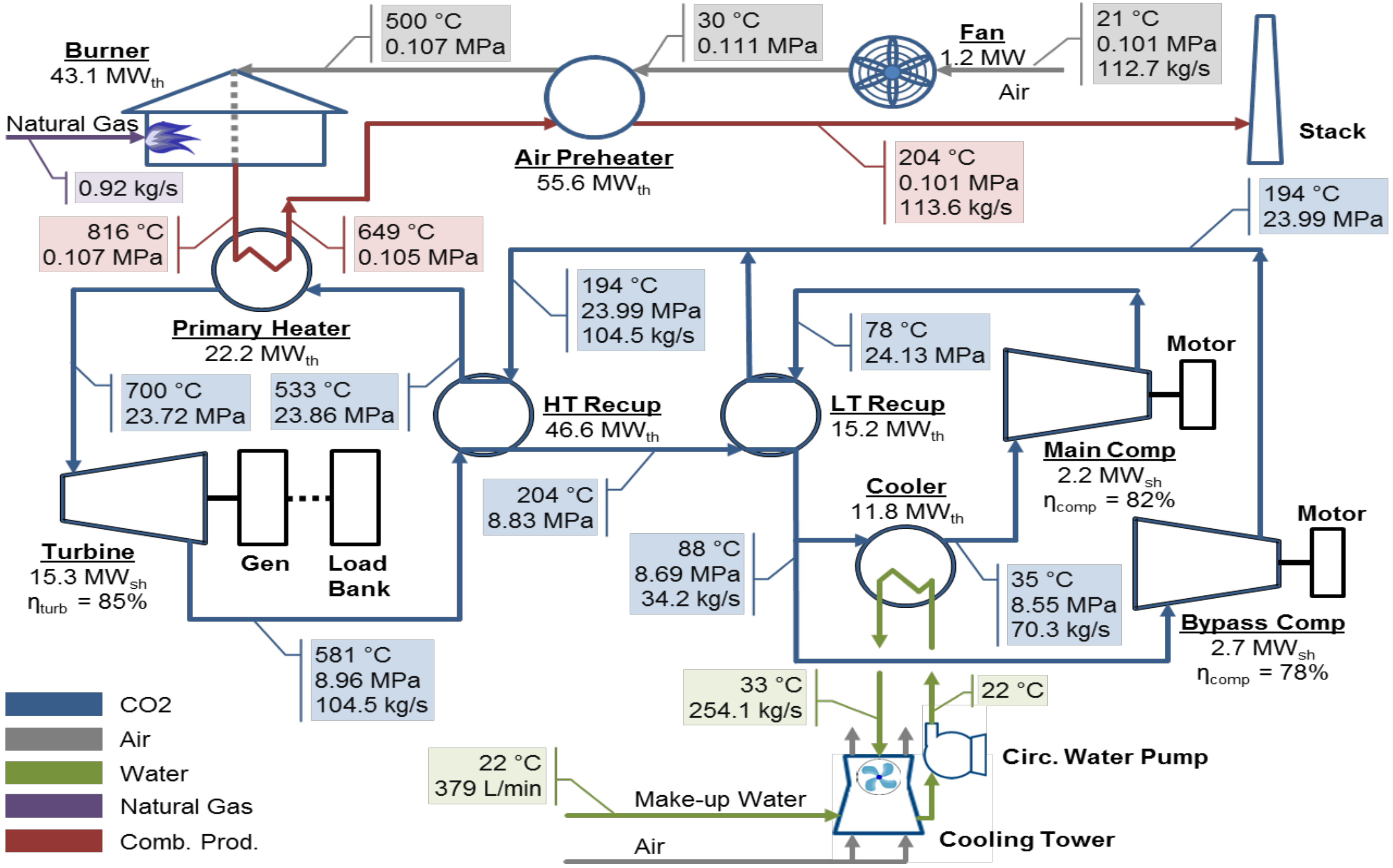
Objectives

- 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

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

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