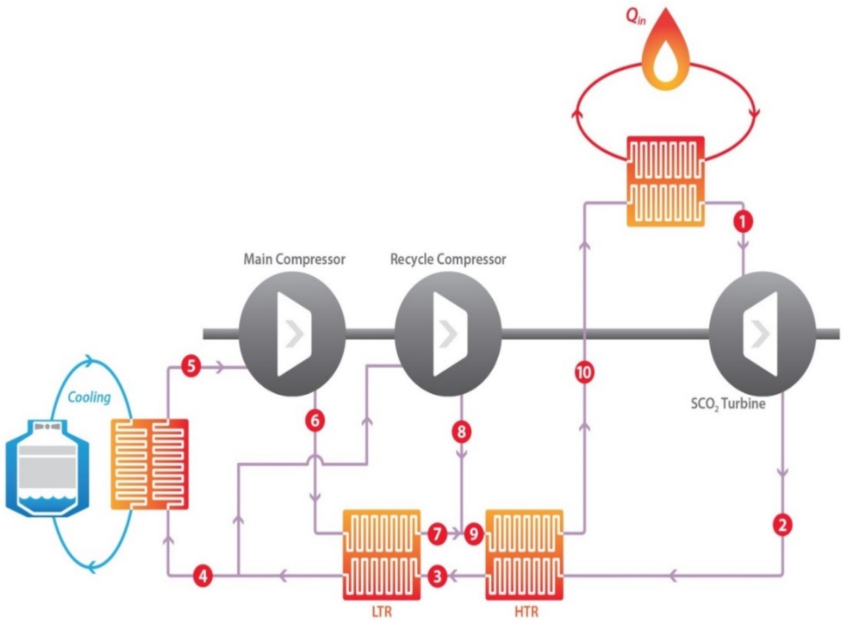
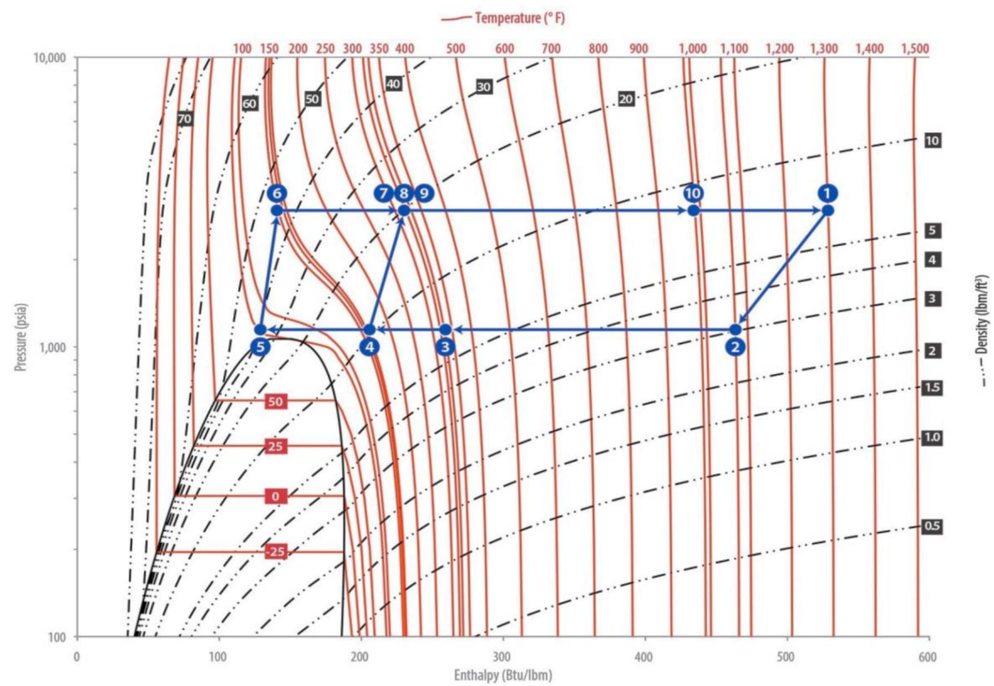




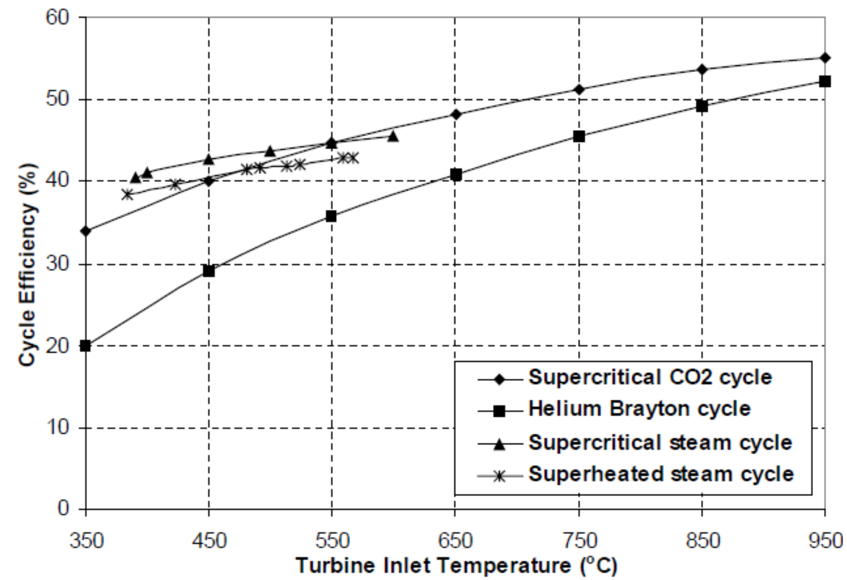
Review of NETL's Supercritical CO_2 (sCO_2) Techno-economic Analyses

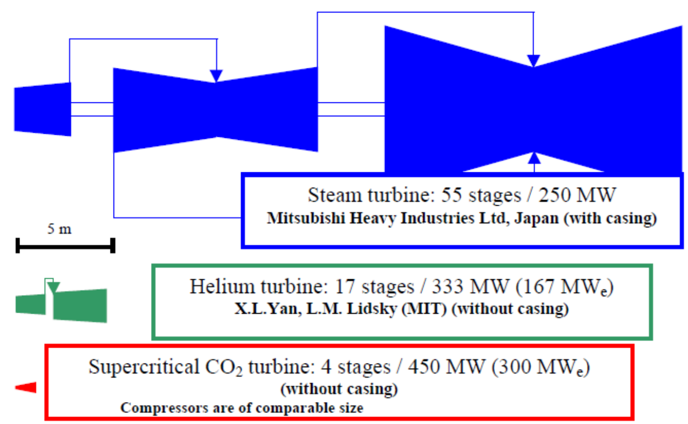
Nathan Weiland, Wally Shelton, Travis Shultz, Charles White

September 20th, 2016

Why Supercritical CO_2 (sCO_2) Power Cycles?

- **Applicable to multiple heat sources (nuclear, solar, fossil, waste heat) for indirect heating**
- **Potential for higher efficiency relative to traditional power cycles**
  - High thermal recuperation rejects less heat to the environment
  - Single phase fluid heat transfer
  - Reduced cycle compression power near the CO_2 critical point
- **Reduced turbomachinery sizes due to higher working fluid density**
- **CO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O**



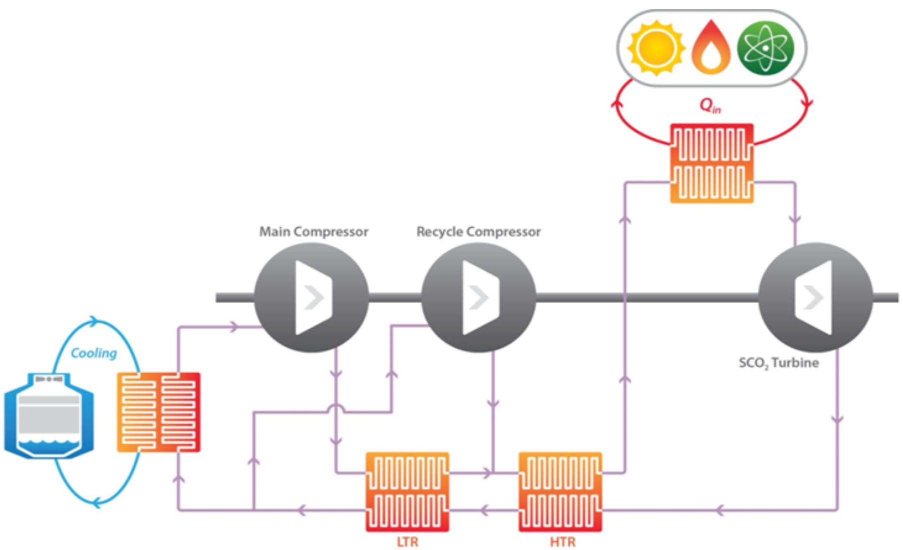


Source of Figures: V. Dostal, M.J. Driscoll, and P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Report MIT-ANP-TR-100, March 2004.

sCO_2 Cycles for Fossil Energy Applications

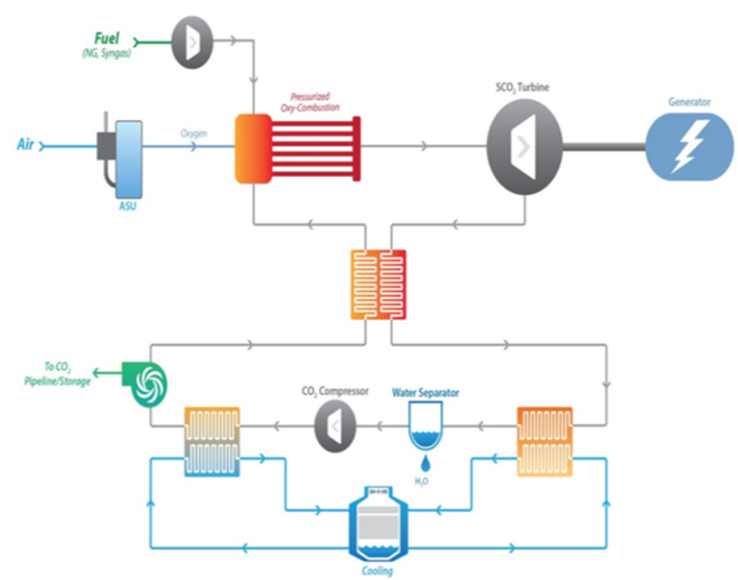
Indirectly-heated cycle

- Applicable to advanced combustion boilers
- Incumbent to beat: USC/AUSC boilers
- High fluid density, low pressure ratio yields compact turbomachinery
- Ideally suited to constant temp heat source
- Adaptable for dry cooling



Directly-heated cycle

- Applicable to IGCC and NGCC
- Incumbent to beat: Adv. F-, H-, or J- class Combined Cycle (NGCC or IGCC) w/ CCS
- Fuel flexible: coal syngas or NG
- 100% CO_2 capture at storage pressure
- Net water producer if air cooled

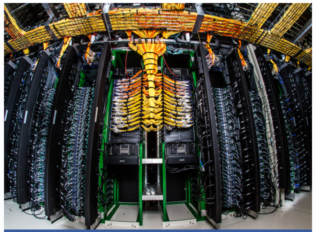


U.S. DOE Fossil Energy sCO_2 Power Cycle R&D Efforts

- **sCO_2 Power Cycles Base Program**
  - Implemented through multiple Fossil Energy programs
  - Combination of extramural projects and internal NETL research and analytical capabilities
    - Turbomachinery
    - Recuperators
    - Oxy-fuel Combustion
    - sCO_2 Heater Integration
    - Materials & Fundamentals
    - Systems Analysis
- **DOE sCO_2 Crosscut Initiative (STEP)**
  - Collaboration between Fossil, Nuclear & Renewable DOE Offices
  - Mission: Address technical issues, reduce risks, and mature technology to accelerate commercialization
  - Objective/goal: Design, build, and test 10 MWe pilot sCO_2 facility (STEP)
    - Conceptual design studies complete
    - $100 Million, 6 year build and test program to start in 2016

NETL Research and Innovation Center

Core Competencies



Computational Science & Engineering

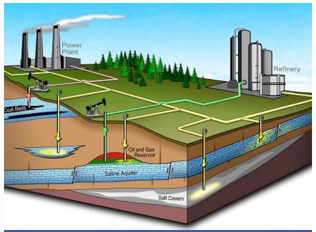
High-Performance Computing

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 & System

Optimization, Validation & Economics

Program Execution & Integration

Strategic Planning

Project Management

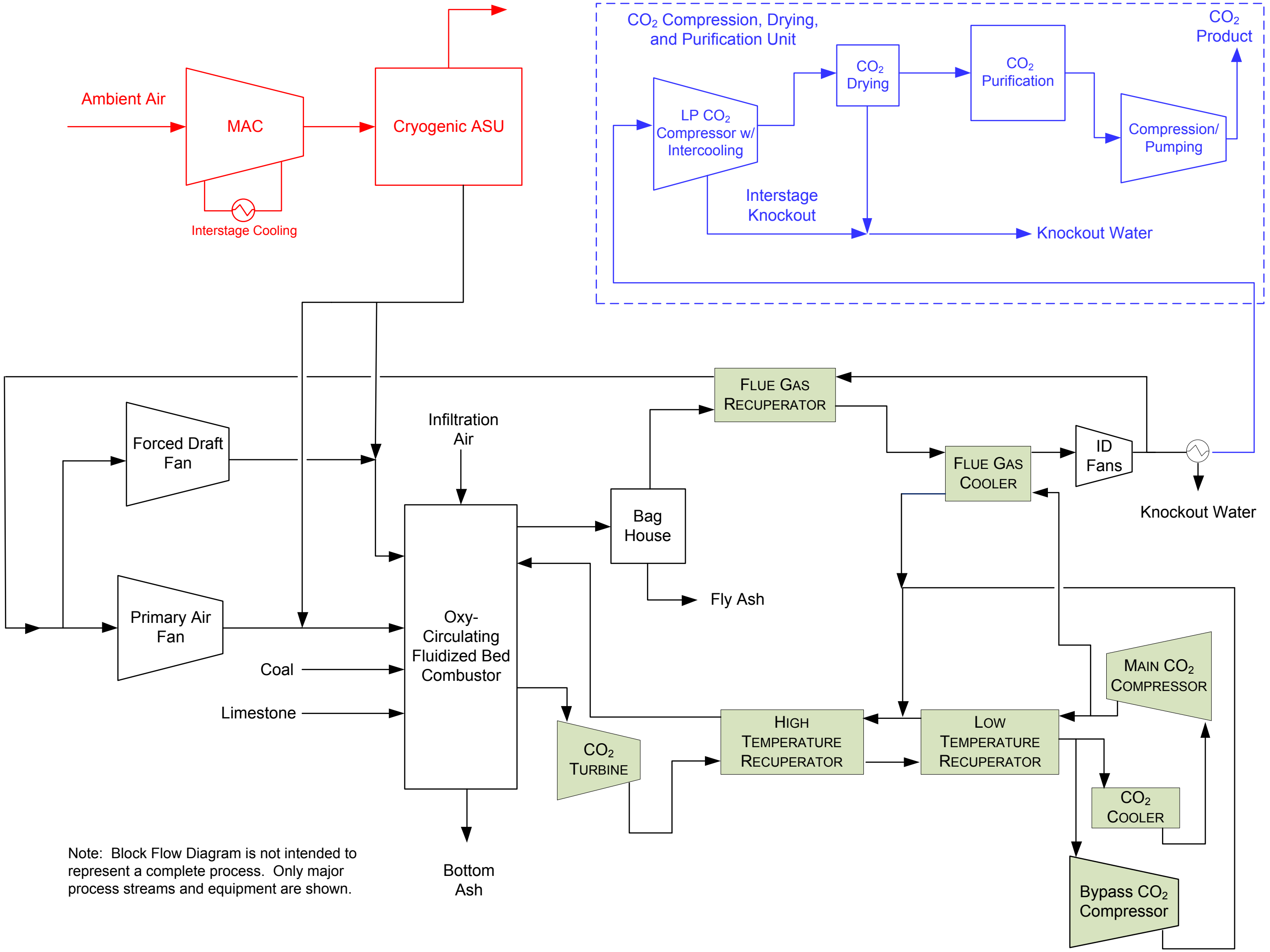
Major sCO_2 Systems Analyses

- **Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO_2 Brayton Cycle**
  – Final report under revision
- **Performance of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle**
  – Plant cost estimate nearing completion
- **Development of a dynamic sCO_2 plant model to assess control mechanisms and transient/part load performance of the 10 MWe STEP demo sCO_2 plant**
  – Preliminary analyses complete, model refinements ongoing

Utility-Scale Indirect sCO_2 Plants
Overview

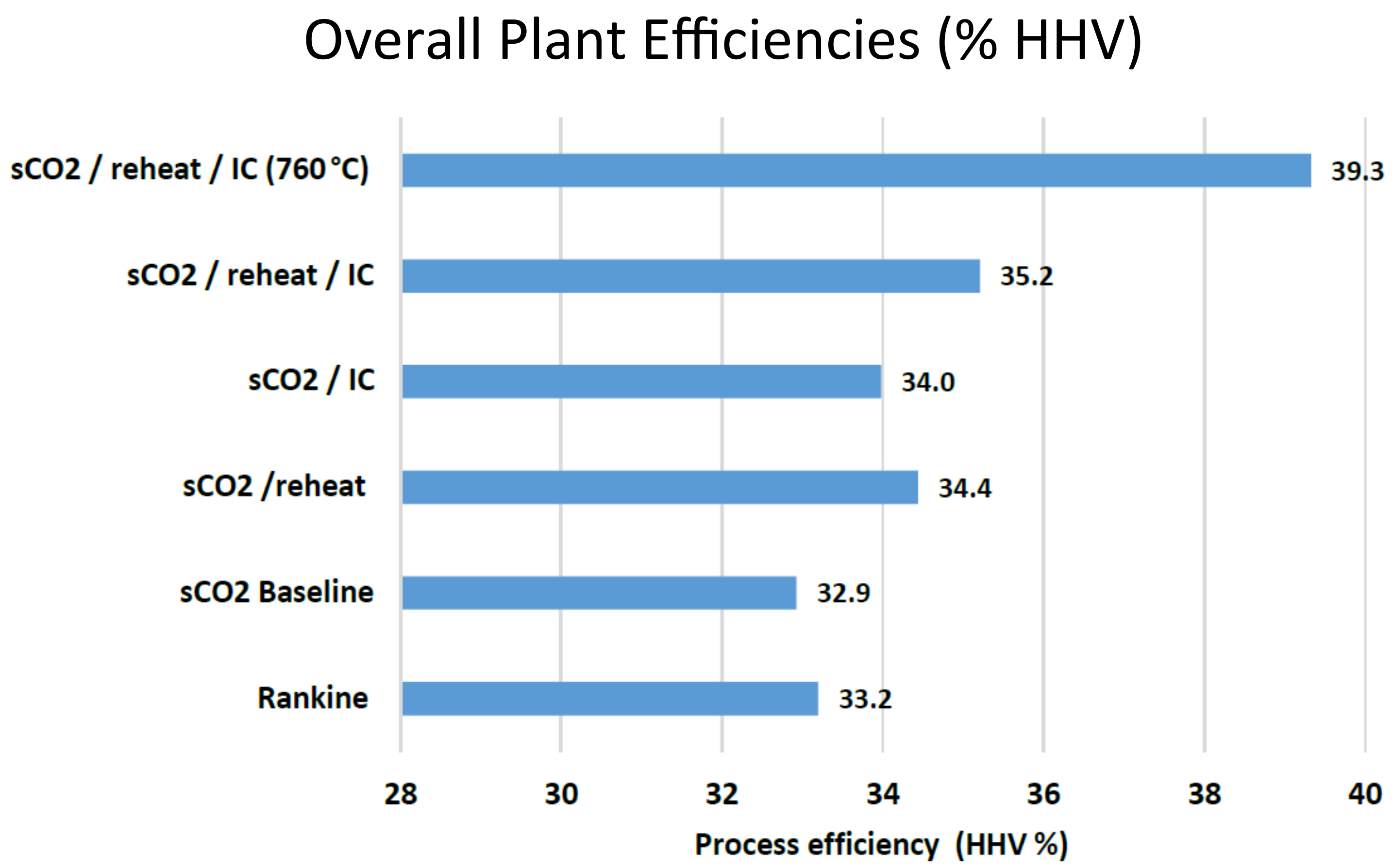
- **Early work shows that the narrow temperature addition window of a recompression sCO_2 Brayton Cycle restricts boiler selection**
  - Modified Oxy-CFB boilers with CCS chosen for analysis
- **Reference: Oxy-Coal-Fired CFB Rankine Cycles with CCS (24.1 MPa/600 °C/620 °C)**
- **Oxy-Coal-Fired CFB sCO_2 Brayton Cycles with CCS: (620°C & 760°C)**
  - Recompression cycle with reheat and/or main compressor intercooling (4 combinations x 2 temperatures)
- **Performance Comparisons**
- **Economic Comparisons & Sensitivity of COE to TPC**
- **Potential for Improved Efficiency – Alternate Cycles**

Oxy-Coal-Fired CFB Recompression sCO_2 Brayton Cycle



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

Indirect sCO_2 Plant Performance

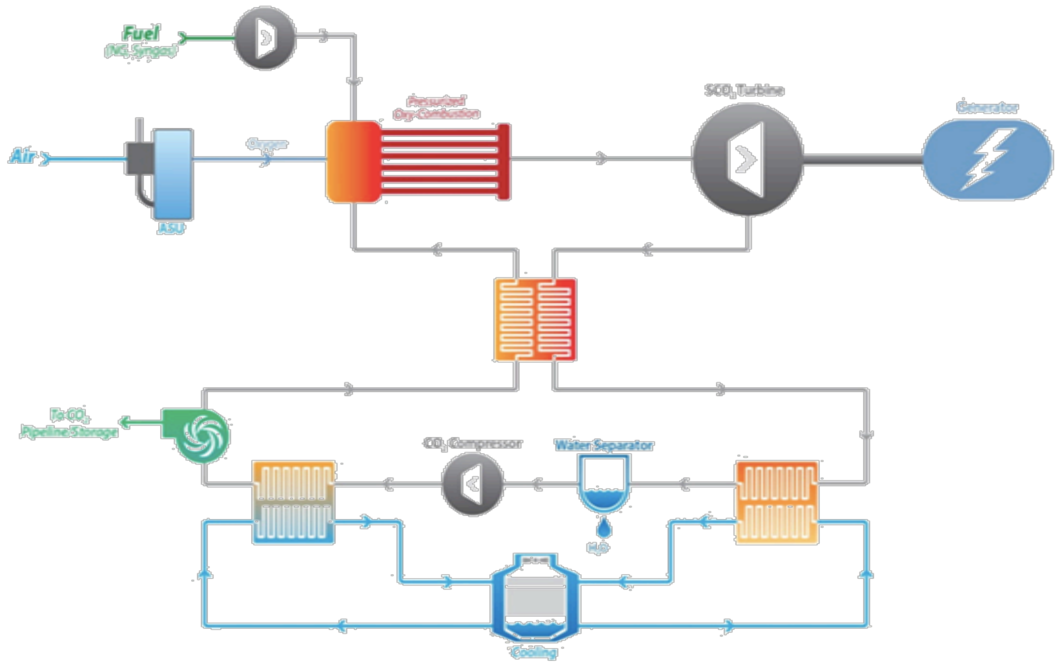


Indirect sCO_2 Summary and Conclusions

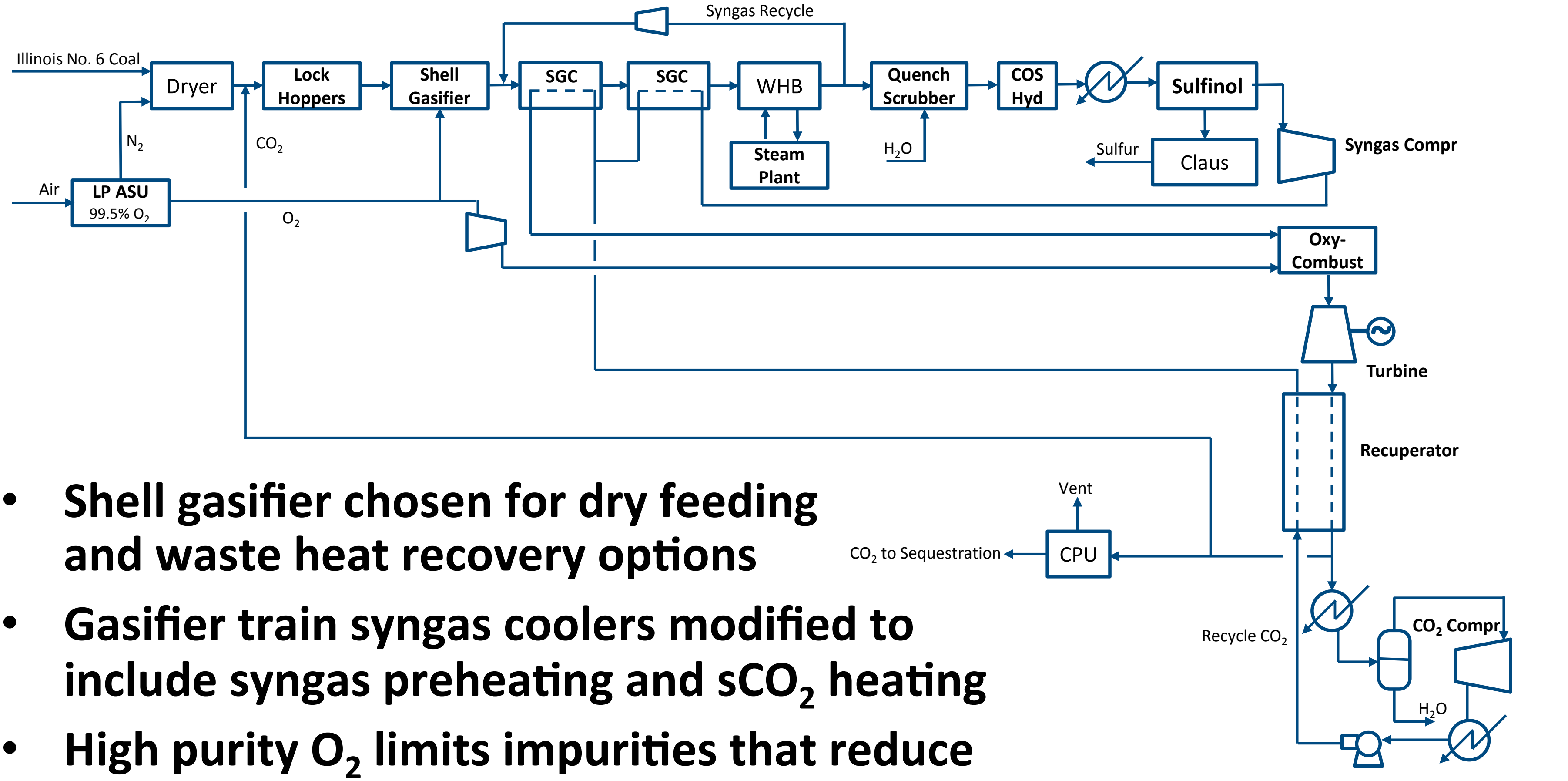
- **Objective - Compare sCO_2 Recompression Brayton Cycle(s) to a SOA Steam Rankine Cycle.**
- **Performance determined for four configurations, all showing performance improvement.**
- **At 620 °C turbine inlet temperature, the reheated and intercooled sCO_2 case shows a ~2 percentage points improvement in plant efficiency compared to the steam Rankine case.**
- **At the higher temperature (760 °C), the comparison to the Steam Rankine Cycle (620 °C) improves in overall efficiency to ~ 6 percentage points.**
- **Further optimizations of the configurations considered may be required to demonstrated an economic advantage.**
  - Condensing CO_2 cycles
  - Partial Cooling sCO_2 Cycle

Direct sCO_2 Cycle Analyses

- **Direct-fired sCO_2 power cycles are attractive due to their high efficiency and inherent ability to capture CO_2 at storage-ready pressures**
- **High pressures lead to high power density and reduced footprint & cost**
- **Study Objectives:**
  - Develop a performance baseline for a syngas-fired direct sCO_2 cycle
  - Analyze sensitivity of performance and cost indicators to sCO_2 cycle parameters



Coal-fired Direct sCO_2 Plant
Block Flow Diagram

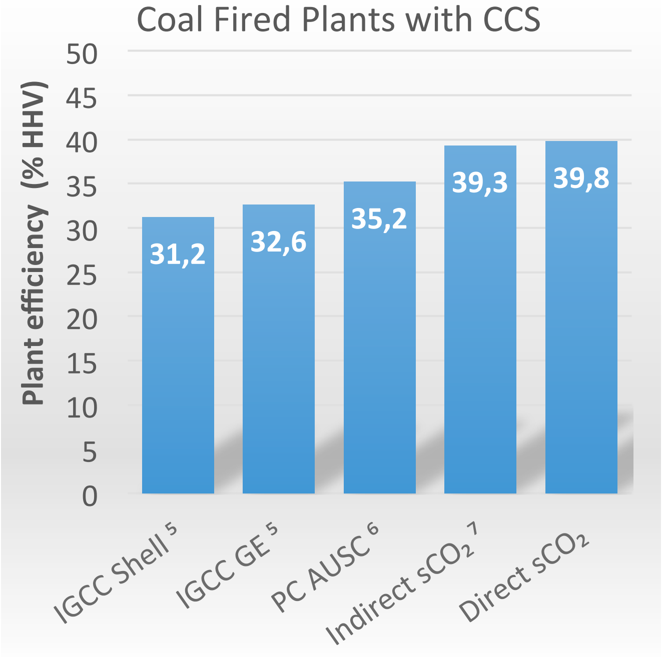


- Shell gasifier chosen for dry feeding and waste heat recovery options
- Gasifier train syngas coolers modified to include syngas preheating and sCO_2 heating
- High purity O_2 limits impurities that reduce direct sCO_2 cycle efficiency
- Syngas oxy-combustion within the sCO_2 cycle

Direct sCO_2 Conclusions and Future Work

- **Conclusions:**
  - Direct coal-fired sCO_2 cycle developed shows improved performance relative to IGCC and other reference cases
  - Capital costs are expected to be lower than IGCC due to replacement of gas turbine and steam bottoming cycle
  - Sensitivity studies provide guidelines for improving performance and reducing costs
- **Future Work**
  - Incorporate the effects of turbine blade cooling flows (completed)
  - Develop cost estimate for the improved baseline case (nearing completion)
  - Extend analyses to development of natural gas-fired direct sCO_2 cycles

Parameter	IGCC	sCO_2 Cycle	EPRI sCO_2 Cycle[2]
Net power output (MWe)	497	595	583
Net plant efficiency (HHV %)	31.2	39.8	39.6
Carbon capture fraction (%)	90	98	99
Captured CO_2 purity (mol% CO_2)	99.99	99.44	98.1

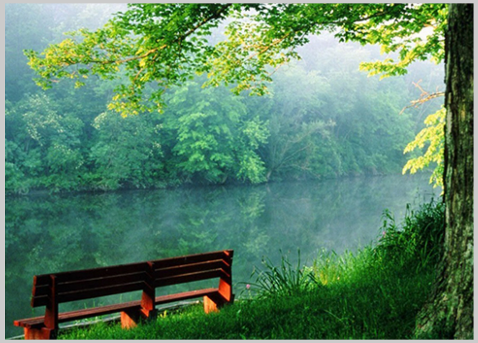


[5] National Energy Technology Laboratory (NETL). (2010, November 2). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Pittsburgh, Pennsylvania.
[6] Weiland, N., and Shelton, W. W. "Systems Analyses of Direct Power Extraction (DPE) and Advanced Ultra-Supercritical (AUSC) Power Plants," Crosscutting Research & Rare Earth Elements Portfolios Review, Pittsburgh, PA, April 18th, 2016.
[7] Shelton, W. W., Weiland, N., White, C., Plunkett, J., and D. Gray. Oxy-coal-fired Circulating Fluid Bed Combustion with a Commercial Utility-size Supercritical CO2 Power Cycle. The 5th International Symposium - Supercritical CO2 Power Cycles. San Antonio, Texas. March 2016.

Other Current and Future sCO_2 Work within SEA

- **Pre-Screening of Indirect sCO_2 Cycle Integration Opportunities (complete)**
  - Evaluated the options for sCO_2 cycle integration with chemical looping combustion, magnetohydrodynamics, and fuel cell systems.
- **Process Systems Engineering Research Team**
  - Pressure-driven Aspen Plus Dynamics model of a 10 MW Indirect sCO_2 Recompression Brayton Cycle
  - Development of a multi-stage radial sCO_2 compressor in Aspen Custom Modeler
- **Development of a 1-D sCO_2 recuperator sizing/costing model**
  - Enables recuperator costing as a function of approach temperature, pressure drop, and materials of construction

It's All About a Clean, Affordable Energy Future

For more information on our sCO_2 efforts, contact:

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