Techno-Economics and Cost Modeling for State-of-the-Art sCO_2 Components

Nathan T. Weiland, NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

NETL-PUB-22690

October 31st, 2019

DOE sCO_2 Workshop 2019, Golden, Colorado

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

NETL's sCO_2 Techno-Economic Analyses

Past, Present, and Future Analyses

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Preliminary commercial-scale sCO_2 techno-economic analyses:**
  - Oxy-coal CFB indirect sCO_2 plant with carbon capture & storage (CCS) – 2017
  - Air-fired coal CFB indirect sCO_2 plant *without* CCS – 2019
  - Coal gasification integrated with direct sCO_2 plant with CCS – 2018
  - Natural gas-fueled direct sCO_2 plant with CCS – 2019
- **Detailed focus area studies for sCO_2 plant cost and efficiency improvements:**
  - sCO_2 component cost scaling study – ASME Turbo Expo 2019 (GT2019-90493)
  - sCO_2 cooling system cost and performance models – beta-testing ongoing
  - sCO_2 cooling system integration study – 3rd European sCO_2 Conference, 2019
  - sCO_2 heat source integration study (indirect sCO_2) – ongoing
  - Air separation unit modeling and integration (direct sCO_2) – ongoing
  - Direct sCO_2 turbine modeling – ongoing
  - Direct sCO_2 integration with alternative gasifiers – beginning Apr. 2020
- **Exemplar coal-fueled indirect sCO_2 plants, with and without CCS – June 2020**
- **Exemplar coal and natural gas direct sCO_2 plants with CCS – June 2021**
- **Techno-economic analysis of a NGCC plant with a sCO_2 bottoming cycle – Sept. 2020**

Tools for sCO_2 Economic Optimization

Presentation Outline

1. **sCO_2 Component Cost Scaling Algorithms**
   - DOE National Laboratory collaboration with Sandia, NREL, INL
2. **sCO_2 Cooling System Cost and Performance Spreadsheet Models**
   - Models available for beta-testing
   - Cost of Electricity (COE) minimization of indirect & direct sCO_2 plants
3. **Primary Heater Cost and Performance Model**
   - Tube bank models determine cost and sCO_2 pressure drop as a function of material selection, tubing outside diameter, and sCO_2 pressure and temperature
   - Roll-up to a coal-fired primary heater cost allows for COE optimization

1. sCO_2 Component Cost Scaling Collaboration

Collaborative work with Sandia, NREL, INL

- **Motivation**
  - Most sCO_2 systems analysis studies to date focus on efficiency-based optimization
  - Commercialization is driven by economics, so plant capital cost must be considered
  - Little component cost data is available to date for this relatively new field
- **Background**
  - Present study is inspired by the work of Carlson et al. (2017 Turbo Expo), which developed cost algorithms for 1-100 MW_e CSP sCO_2 plants[1]
  - Present study expands upon this work by leveraging the collective resources of the U. S. Department of Energy (DOE) National Laboratories, with sCO_2 component vendor costs spanning multiple applications (nuclear, fossil, solar) and size ranges (5-750 MW_e)
- **Resulting cost correlations are reasonably accurate and comprehensive, and should enable a shift from efficiency-based to cost of electricity-based sCO_2 plant optimization, accelerating commercialization of sCO_2 cycles**
- **Developed cost algorithms include cost scaling factors for high temperature, and have been validated and refined through industry feedback**

[1] Carlson, Matthew D., Bobby M. Middleton, and Clifford K. Ho. "Techno-Economic Comparison of Solar-Driven SCO_2 Brayton Cycles Using Component Cost Models Baselined With Vendor Data and Estimates", *Proceedings of the ASME 2017 11th International Conference on Energy Sustainability*, Charlotte, North Carolina, 2017.

Development of Cost Algorithms

Source of Vendor Quotes

- **Vendor quotes were collected for sCO_2-specific components from a wide range of DOE sources:**
  - Internal quotes from NETL, SNL, and NREL
  - Results from DOE-funded sCO_2 plant design studies
  - All quotes are for indirect sCO_2 primary cycle applications
- **Vendor confidentiality was maintained when exchanging quotes across each DOE laboratory, and in reporting results – no vendor data points are shared**
- **Total 129 vendor quotes were gathered from DOE-wide collaboration**
  - Of these, some vendor quotes (36) were not included in curve fitting due to lack of needed information or very high/low costs relative to similar quotes
- **Non-recurring engineering and component installation costs have been separated to arrive at equipment-only costs**

Description of Cost Algorithms

General Cost Correlation Form

- **Power law form is used for developing new cost algorithms**
  - Appropriate scaling parameter (SP) is selected for different components
  - For recuperators and coolers, UA scaling parameter calculated from 1-D models
- **Temperature correction factor (f_T) is included for certain components to account for increase in cost with temperature**
  - Temperature break point (T_{bp}) is set to 550 °C
- **Other correction factors to account for influence of operating pressures, pressure drops on the component costs are not included in the current study, but may be considered in future studies**

$$C = a\,SP^b \text{ x } f_T$$

$$f_T = \begin{cases} 1 & \textbf{\textit{if}}\ T_{max} < T_{bp} \\ 1 + c\left(T_{max} - T_{bp}\right) + d\left(T_{max} - T_{bp}\right)^2 & \textbf{\textit{if}}\ T_{max} \geq T_{bp} \end{cases}$$

Description of Cost Algorithms

Methodology – Confidence Rating

- **Confidence Rating (CR) is assigned to each vendor quote to properly account for quality of the quote**
  - Similar to AACE International cost estimate classification[2]
- **Quote Confidence Ratings are used in the curve-fitting procedure and uncertainty quantification**
  - Curve fitting minimizes CR-weighted average absolute error between the actual quotes and the cost algorithms
  - Lends statistical confidence to curve fits in which no vendor data points are shown
- **Uncertainty associated with the cost algorithm has two independent sources of error:**
  - Uncertainty associated with vendor quote (U_{CR})
  - Cost algorithm weighted correlation error (how well the model fits the vendor data)

Confidence Rating (CR)	1	2	3	4	5
AACE Class	5	4	3	2	1
Uncertainty – Low (U_{CR})	-50%	-30%	-20%	-15%	-10%
Uncertainty – High (U_{CR})	+100%	+50%	+30%	+20%	+15%
Quote Includes:					
sCO_2-specific	N	Y	Y	Y	Y
Performance estimates	N	M	Y	Y	Y
Cost itemization	N	N	M	Y	Y
Materials of construction	N	N	M	Y	Y
Size and weight	N	N	M	M	Y
Drawings	N	N	N	M	Y
Installation costs	N	N	N	M	Y

Y = Yes; M = Maybe; N = No

[2] AACE International Recommended Practice Number 16R-90, "Conducting Technical and Economic Evaluations -- As Applied for the Process and Utility Industries; TCM Framework 7.3 -- Cost Estimating and Budgeting," AACE, 2003.

Summary of Cost Algorithms

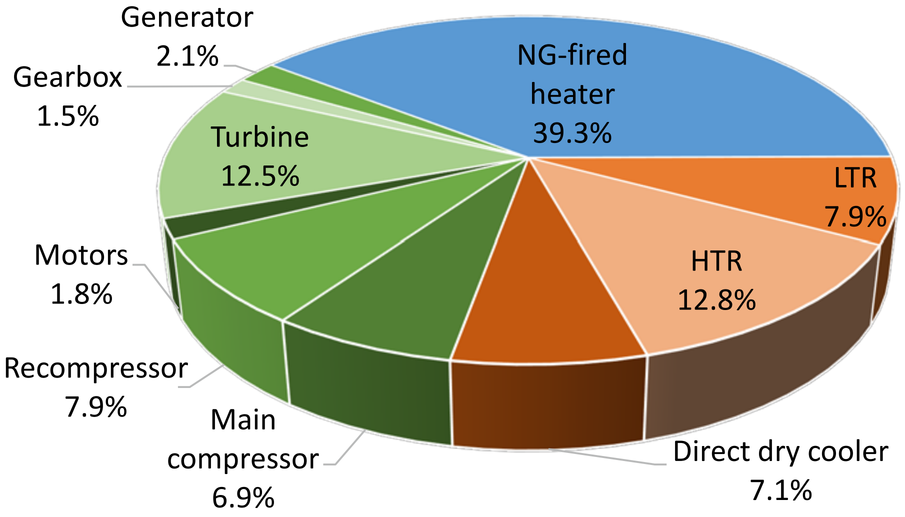
$$C = a\,SP^{b} \times f_T \qquad f_T = \begin{cases} 1 & \textbf{if}\ T_{max} < 550\,^{\circ}C \\ 1 + c\left(T_{max} - T_{bp}\right) + d\left(T_{max} - T_{bp}\right)^2 & \textbf{if}\ T_{max} \geq 550\,^{\circ}C \end{cases}$$

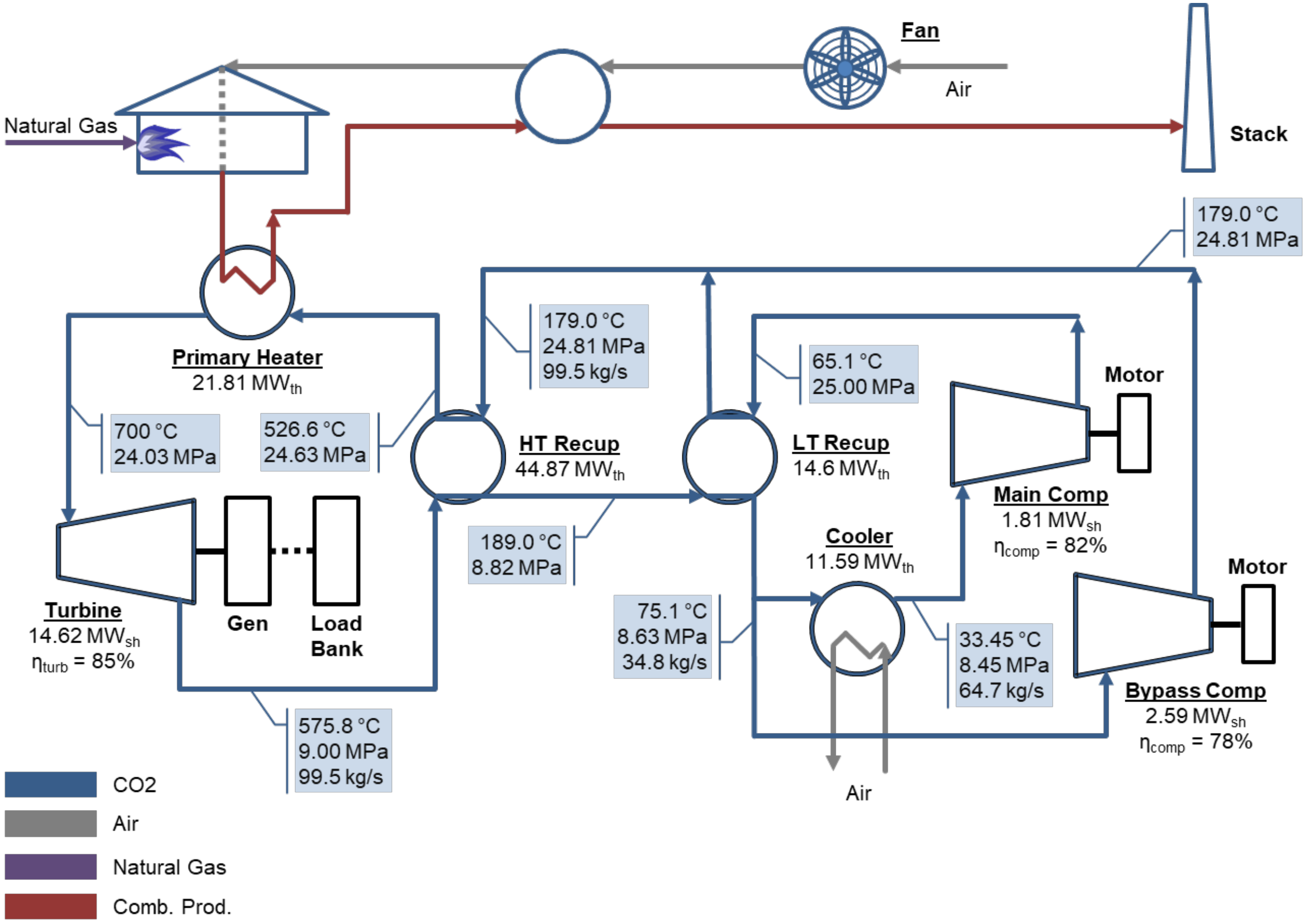
Component	Scaling Parameter (Units)	Coefficients				Database Range (Range of Validity)	Uncertainty Range	Installation (Materials & Labor)
		a	b	c	d			
Coal-fired heaters	Q (MW_{th})	820,800	0.7327	0	5.4e-5	187 to 1,450 MW_{th}	-23% to +26%	50%
Coal-fired heaters	UA (MW_{th})	1,248	0.8071	0	5.3e-6	7.4e5 to 5.9e6 W/K	-16% to +21%	50%
Natural gas-fired heaters	Q (MW_{th})	632,900	0.60	0	5.4e-5	10 to 50 MW_{th}	-25% to +33%	20%
Recuperators	UA (W/K)	49.45	0.7544	0.02141	0	1.6e5 to 2.15e8 W/K	-31% to +38%	5%
Direct air coolers	UA (W/K)	32.88	0.75	0	0	8.6e5 to 7.5e7 W/K	-25% to +28%	20%
Radial turbines	$\dot{W}_{sh}$ (MW_{sh})	406,200	0.8	0	1.137e-5	8 to 35 MW_{sh}	-32% to +51%	20%
Axial turbines	$\dot{W}_{sh}$ (MW_{sh})	182,600	0.5561	0	1.106e-4	10 to 750 MW_{sh}	-25% to +30%	20%
IG centrifugal compressors	$\dot{W}_{sh}$ (MW_{sh})	1,230,000	0.3992	0	0	1.5 to 200 MW_{sh}	-40% to +48%	20%
Barrel type compressors	$\dot{V}_{in}$ (m^3/s)	6,220,000	0.1114	0	0	0.1 to 2.4 m^3/s	-30% to +50%	20%
Gearboxes	$\dot{W}_{sh}$ (MW_{sh})	177,200	0.2434	0	0	4 to 10 MW_{sh}	-15% to +20%	20%
Generators	$\dot{W}_e$ (MW_e)	108,900	0.5463	0	0	4 to 750 MW_e	-19% to +23%	20%
Explosion proof motors	$\dot{W}_e$ (MW_e)	131,400	0.5611	0	0	0.00075 to 2.8 MW_e	-15% to +20%	20%
Synchronous motors	$\dot{W}_e$ (MW_e)	211,400	0.6227	0	0	0.15 to 15 MW_e	-15% to +20%	20%
Open drip-proof motors	$\dot{W}_e$ (MW_e)	399,400	0.6062	0	0	0.00075 to 37 MW_e	-15% to +20%	20%

Application of Cost Algorithms

Baseline 10 MW_e plant cost

- **Operating conditions for a 10 MW_e plant taken from Zitney & Liese[3]**
  - Turbine Inlet: 700 °C, 24 MPa
- **sCO_2 power block installed cost, excluding piping: $27.1M**
  - 1.4% increase in cost with turbo-driven compressors



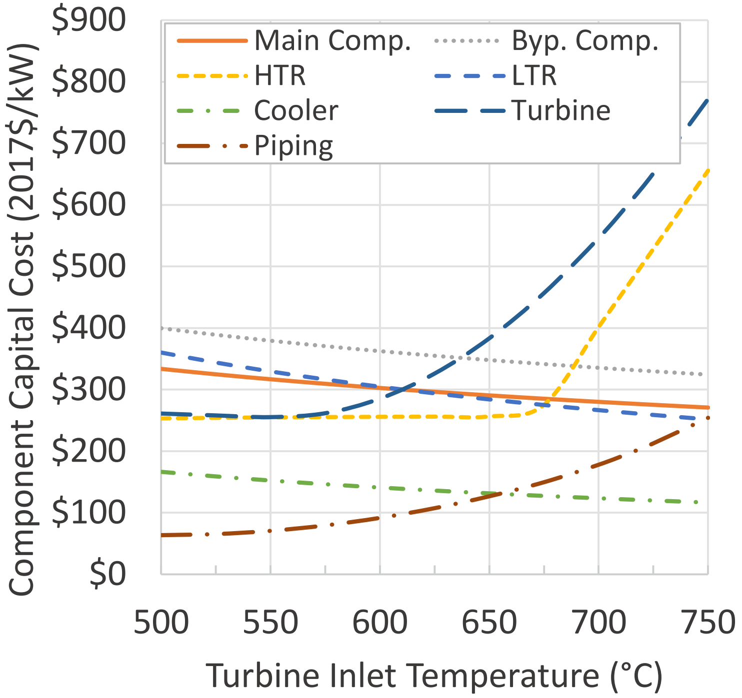


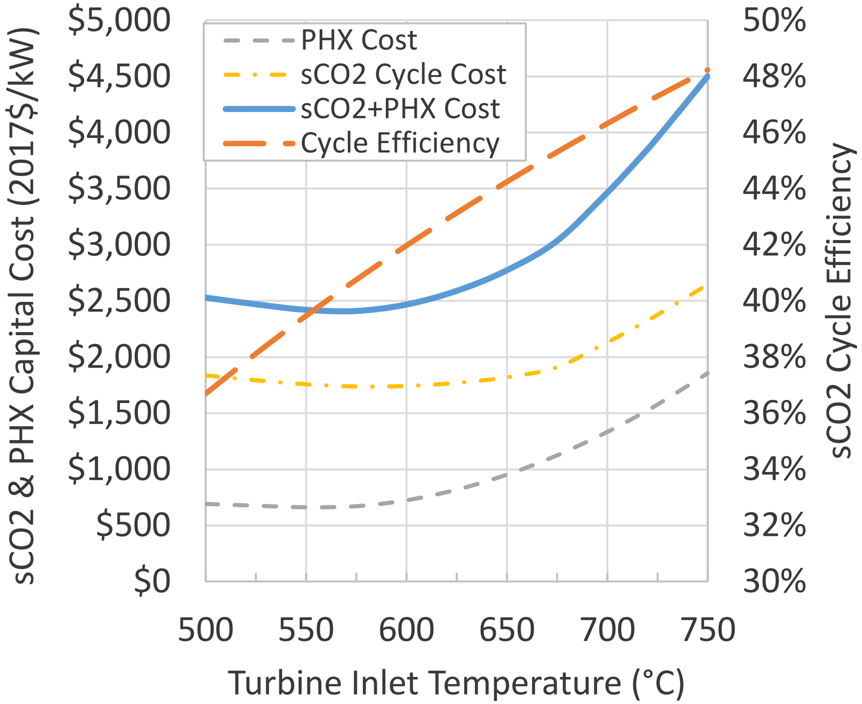
[3] S. E. Zitney and E. A. Liese, "Dynamic Modeling and Simulation of a 10 MWe Supercritical CO2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis," in The 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, 2018.

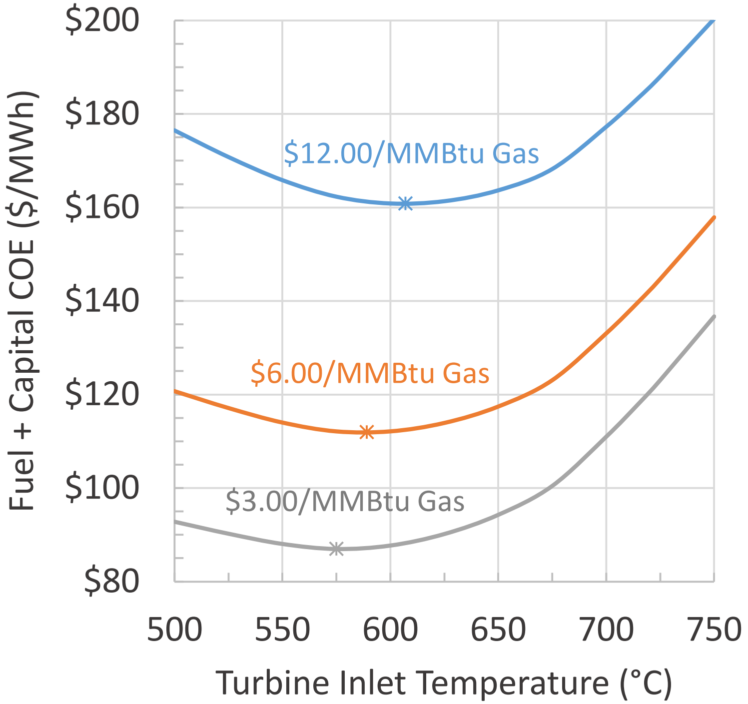
Example Application of Cost Algorithms

Sensitivity of 10 MW_e Plant to Turbine Inlet Temperature

- **Using a spreadsheet cycle model developed with REFPROP, sensitivity analysis was conducted using the new cost algorithms (maintaining 10 MW_e net plant output)**
- **Optimized plant balances annualized capital cost against expected fuel cost**
- **Economics assume 80% capacity factor, 30 yr. plant life, scaled capital cost**







sCO_2 Component Costs - Future Work

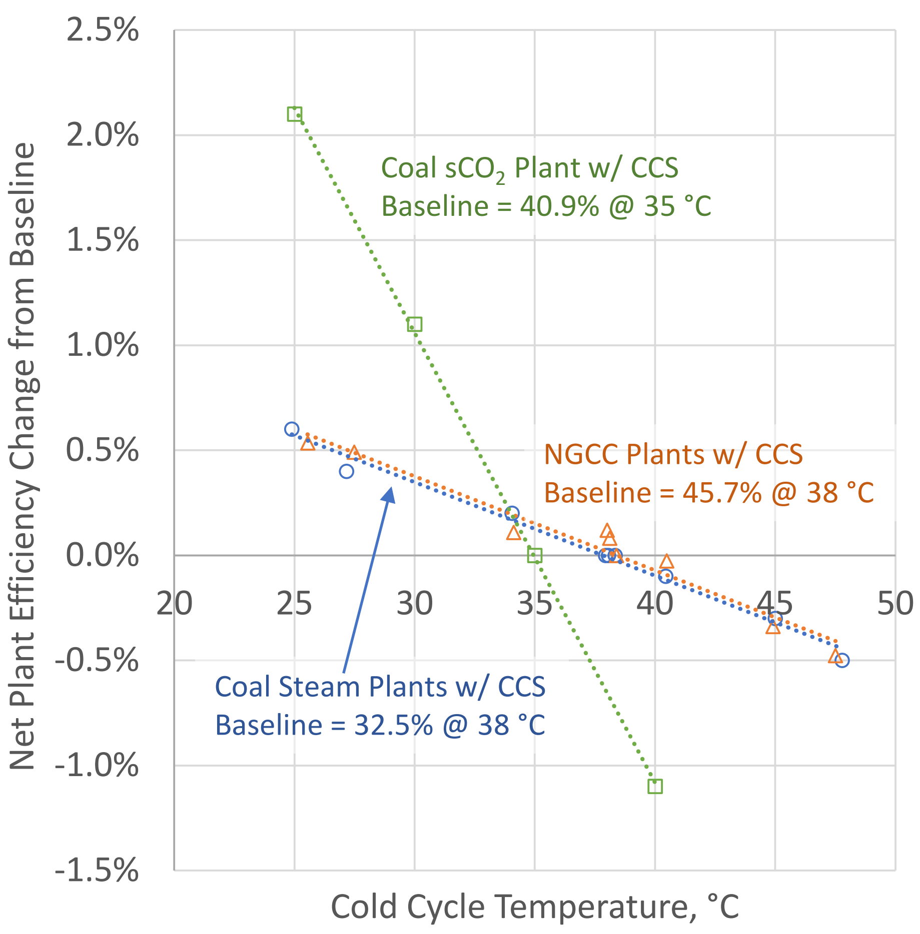
Potential Improvements and Additional Cost Algorithms

- **Extend the recuperator cost algorithm to higher temperatures (> 585 °C) for higher turbine inlet temperature indirect and direct sCO_2 plant applications**
  - Additional pressure drop cost scaling factor might also be included
- **Develop separate cost algorithm for sCO_2-to-water coolers, which should be lower cost than recuperators**
- **Revise high-uncertainty cost correlations for radial turbines, integrally-geared and barrel-type compressors with additional high-quality vendor quotes**
- **Extend gearbox cost algorithm size range to ~60 MW_{sh} (currently 4 to 10 MW_{sh})**
- **Develop cost algorithms for other indirect sCO_2 primary heaters**
  - Waste heat recovery applications
  - Coal-fired CFB (Oxy-fired, Air-fired)
  - CSP applications
  - Nuclear
- **Develop cost algorithms for other turbines and supporting components**
  - Turbine stop and control valves
  - Direct sCO_2 combustor and turbine

2. sCO_2 Cooling System Modeling

Motivation

- **The efficiency of sCO_2 power cycles is about 5 times more sensitive to cold cycle temperature than steam- or gas turbine-based power cycles**
  - sCO_2 compression power is sensitive to inlet conditions near the CO_2 critical temperature (31 °C)
  - Addition of low-cost cooling capacity can lower the compressor inlet temperature
- **Conventional cooling system design principles based on steam power cycles need to be reconsidered for sCO_2 power cycles**
  - Opportunity to significantly improve sCO_2 plant performance through cooling system design
  - Economic re-optimization of cooling system capacity and operating parameters



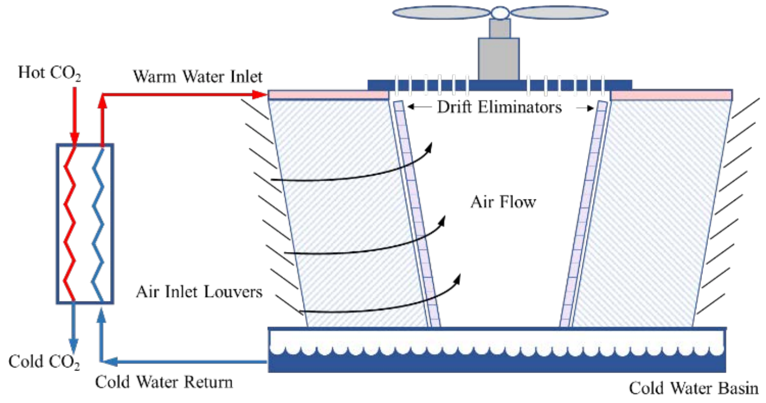
sCO_2 Cooling System Models

NATIONAL ENERGY TECHNOLOGY LABORATORY

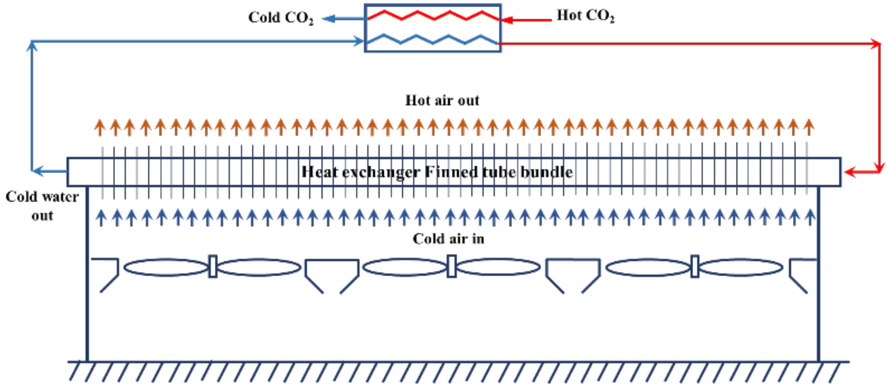
- **Developed performance and cost spreadsheet models for four cooler types**
  - Direct and indirect (via water) sCO_2 cooling
    - Includes water/sCO_2 heat exchanger, if needed
  - Wet and dry cooling technologies
  - Applicable to indirect and direct sCO_2 power cycles
- **Applied results to an existing plant design, optimized for different cold sCO_2 temperatures from 20-40 °C**

Input Parameters	Output Parameters
CO_2 inlet temperature & pressure	Air flow rate and outlet temperature
CO_2 outlet temperature	Fan power consumption
Ambient temperature, pressure & humidity	Circulating water pump power consumption
Cooling duty	Circulating water flow rate
Cooling range	Water make-up requirement
Cooling approach	Cooler construction cost

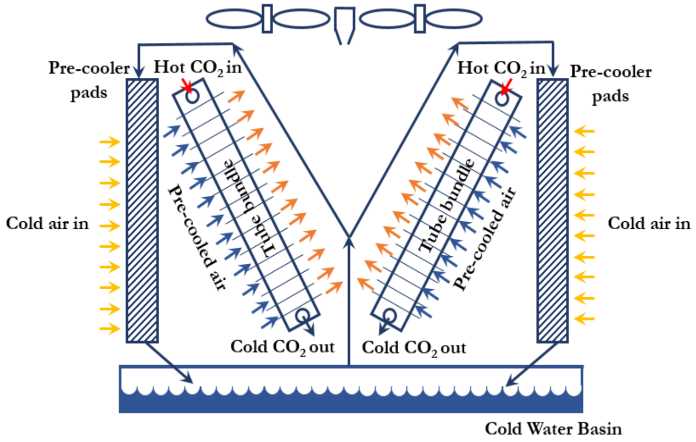
Wet Cooling Tower



Indirect Dry Cooler



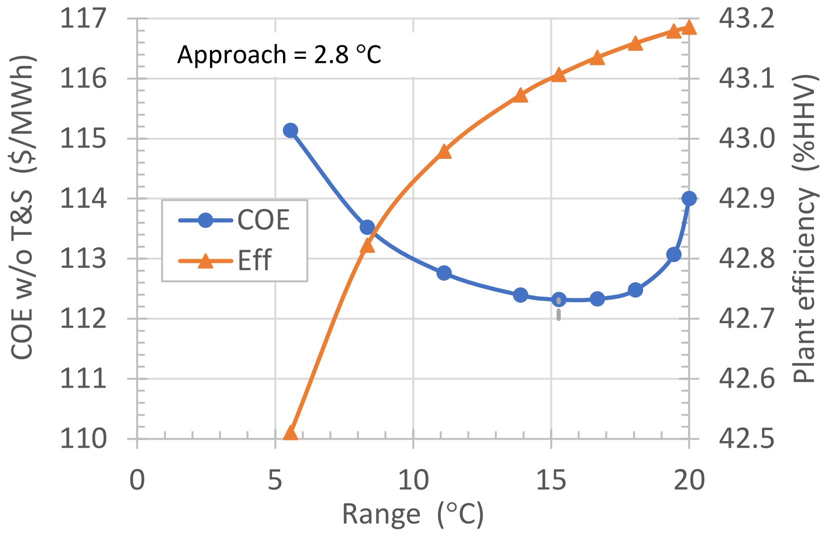
Direct and/or Adiabatic Cooler

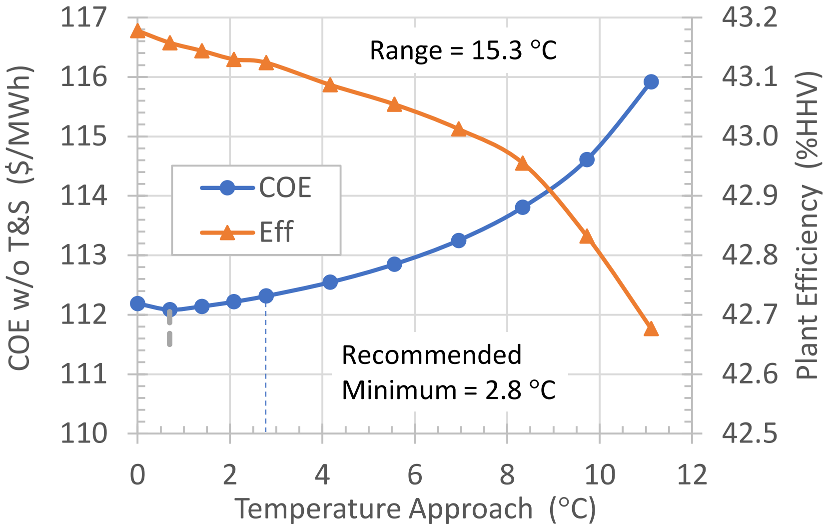


Example Results: Wet Cooling Tower

Efficiency and COE Sensitivity to Range and Approach

- **Representative results shown for a cooler outlet temperature of 25 °C**
- **For increasing cooling water Range:**
  - Water flow decreases, reducing cooling fan and water pump power consumption, increasing efficiency
  - Water/CO_2 heat exchanger capital costs increase due to reduced driving forces and higher heat transfer area
  - Cooling tower capital costs decrease
  - Opposing cost trends minimize the plant's COE for a cooling tower range of 15.3 °C in this example case.
- **For increasing Temperature Approach:**
  - Fan and pump power increase, reducing efficiency
  - Smaller cooling tower is needed, but water/CO_2 heat exchanger costs increase rapidly
  - Recommended minimum approach is 2.8 °C (5 °F)

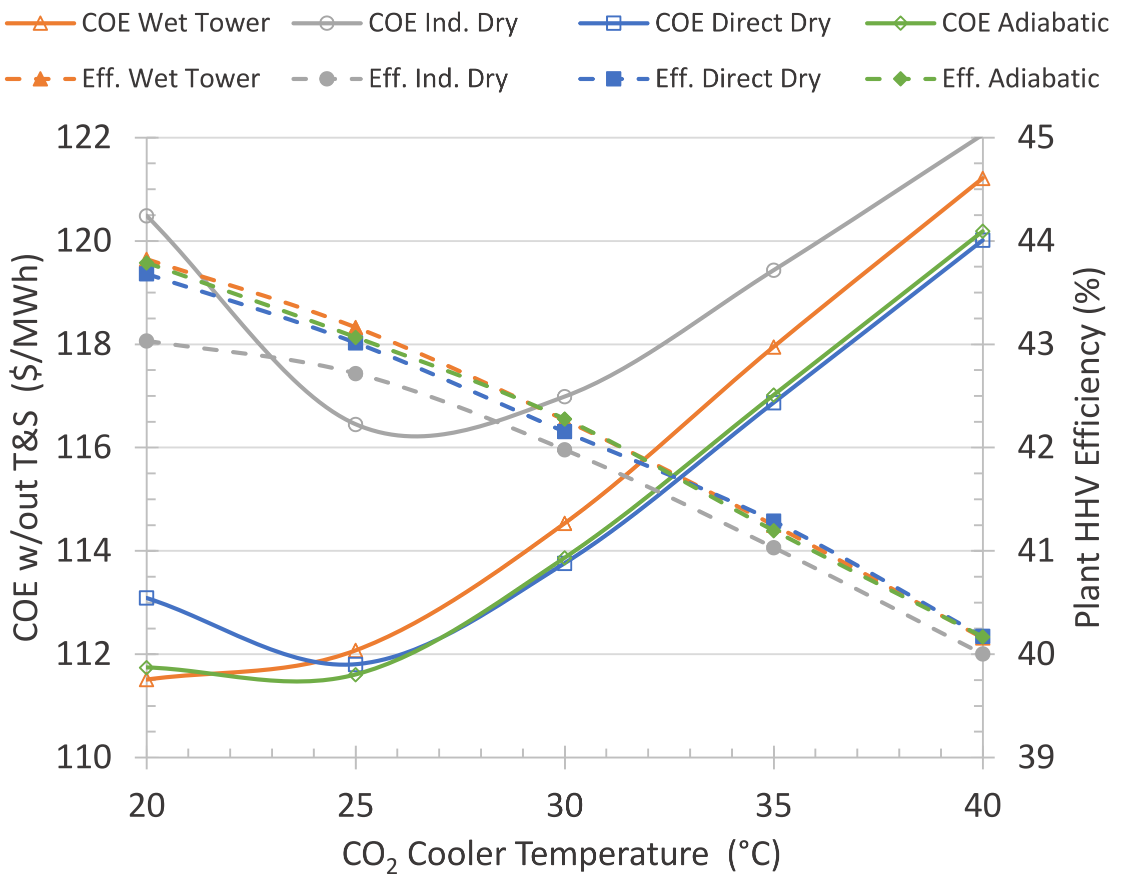




Cooling Technology Comparison

Efficiency and COE Optimization Results

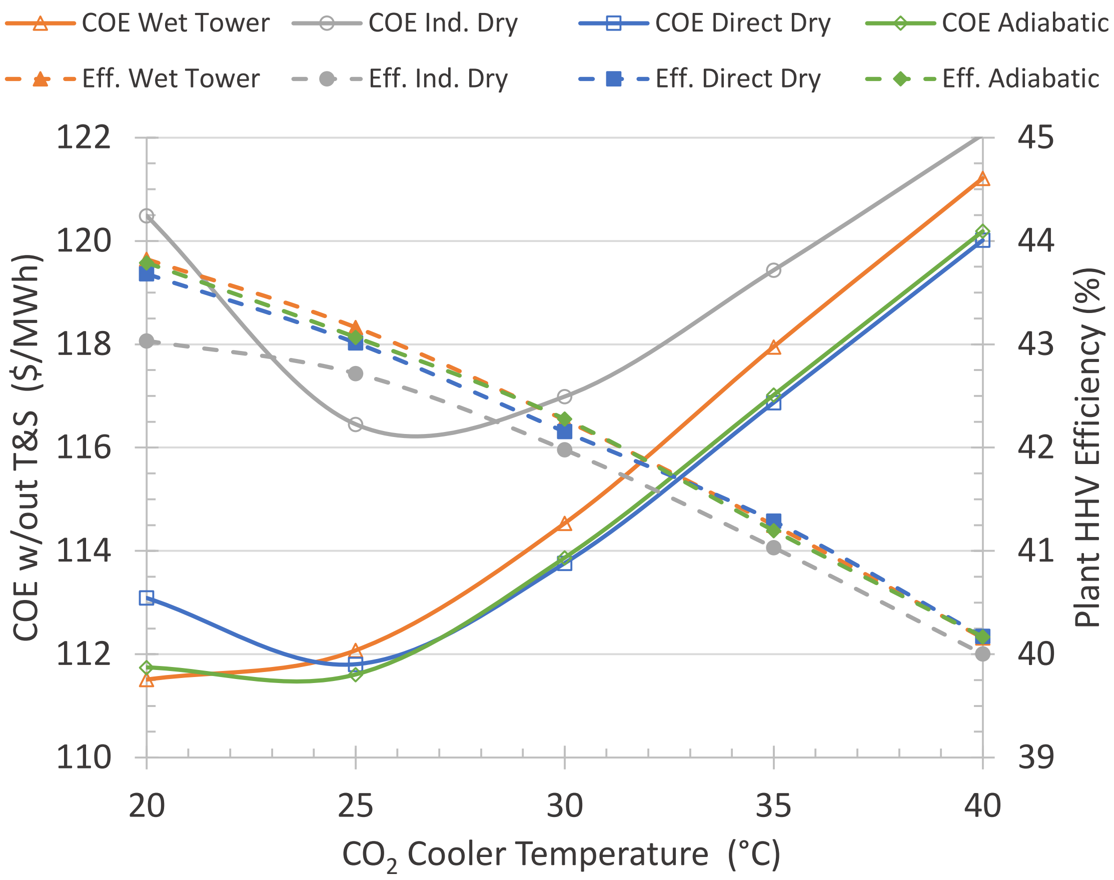
- **Cooler operating conditions optimized for COE at each cooler temperature**
  - Optimized results are valid only for the plant design and ambient conditions selected
- **CO_2 cooler exit temperatures of 20-25 °C minimize COE**
- **Plant efficiency improves 3.0 – 3.5 %points, and the plant COE is reduced by as much as 8%, by decreasing the CO_2 cooler temperature from 40 to 20 °C**
- **Cooler Modeling Impacts:**
  - Cooling system optimization can be applied to all sCO_2 plant types
  - Published cooler cost and performance modeling tools enables COE optimization at any sCO_2 plant site given its ambient conditions



Cooling Technology Comparison

Efficiency and COE Optimization Results (cont.)

- **Indirect dry cooling is non-competitive**
- **Wet cooling towers are attractive, but have the highest water consumption**
- **Performance of direct dry and adiabatic cooling technologies are similar until cooler temperatures approach ambient**
- **Adiabatic cooling used in CO_2 refrigeration systems may be the most applicable to sCO_2 power cycles**
  - Ability to provide the coldest sCO_2 temperatures for a given ambient temperature
  - Flexibility to use water only as needed during hot conditions
  - ~40% less water consumption than wet cooling towers (using present study's assumptions)



3. sCO_2 Primary Heater Integration

- **<u>Motivation</u>: For fossil-fueled systems, the primary heater costs 1.3 – 2.6 times the *entire* sCO_2 power cycle, and incurs high sCO_2 pressure drops.**
  - Little has been done to reduce primary heater costs and pressure drops through sCO_2 cycle architecture changes and thermal integration
- **<u>Objective</u>: Determination of an optimized thermal integration strategy between the primary heater and indirect sCO_2 cycle to maximize plant performance and reduce Cost of Electricity (COE).**
- **<u>Approach</u>: Develop primary heat cost and performance relationships as a function of temperature, pressure, tubing diameter, and material selection**
  - Exercise performance and cost model to minimize plant COE for recompression and partial cooling sCO_2 cycles, both with and without reheat
- **<u>Impact</u>: Improved economics and commercialization potential of coal-fired sCO_2 power cycles relative to steam**

Circulating Fluidized Bed (CFB) Design Tool

CFB cost breakdown for steam or sCO_2 power cycles

- **Goal is to calculate CFB pressure drop and estimate bottoms-up CFB cost for sCO_2 power cycles with reasonable accuracy**
- **A model was developed that can be used to**
  - Understand the impact of varying pressure drop, turbine inlet pressure and temperature on CFB capital cost
  - More accurately compare the performance and economics of recompression vs partial cooling cycle
- **CFB data was gathered for eight STEAMPRO simulations of air-fired CFB steam Rankine plants with reheat to understand the impact of heat duty, turbine inlet temperature (TIT) and tube bank arrangement**

CFB cost sub-accounts	Description
SA1	Furnace radiative tube banks
SA2	Convective tube banks
SA3	Interconnecting piping, cyclones, refractory etc.
SA4	Tubular oxidant pre-heater (scaled to *UA*)
SA5	Rest of the CFB (scaled to heat duty) (Soot blowers, ducts, feeders, fans, structural)

SA1 & SA2 are a function of tube sizes, tube material, working fluid, temperature, pressure and driving forces

These sub-accounts are assumed to be independent of the working fluid (same for steam and sCO_2 cycles)

Tube Bank Sizing and Cost Model

Overview of the model

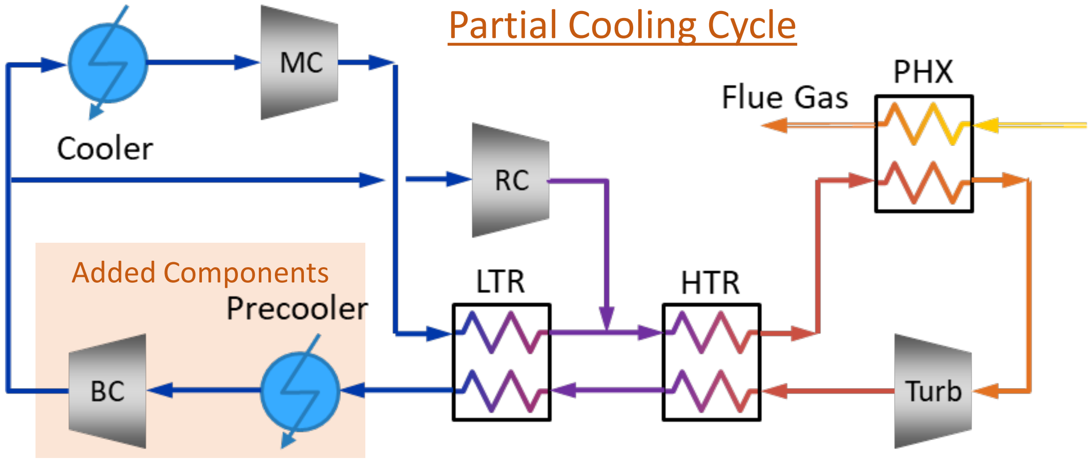
- **A tube bank sizing and cost model was developed as part of the CFB design tool to calculate the pressure drop and cost of tube banks (SA1 and SA2)**
  - Allows user to select several alloys for tube, tube outer diameter
  - Calculates required tube wall thickness from ASME code, heat transfer area, working fluid pressure drop (either steam/sCO_2) for specified process conditions
  - Tube bank cost scaled from $/lb tubing material costs + 50% fabrication cost
  - Model validated against tube bank data from STEAMPRO

Model Inputs	Model Outputs
Steam/sCO_2 flow rate	Tube bank heat duty
Steam/sCO_2 inlet pressure and temperature	
Steam/sCO_2 outlet temperature	
Flue gas inlet temperature	Driving force ($LMTD$)
Flue gas outlet temperature	Steam/sCO_2 pressure drop
Tube material	Required heat transfer area
Tube outer diameter	Tube wall thickness and maximum wall temperature
Tube length	Tube bank cost

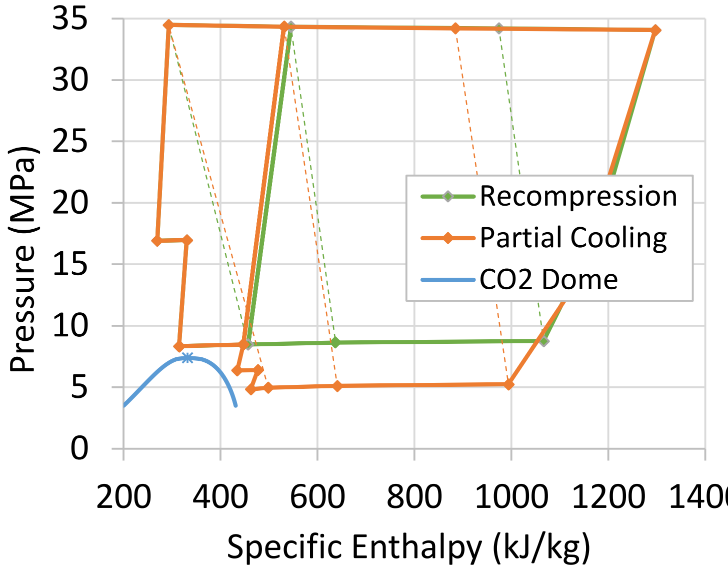
sCO_2 Heat Source Integration Study

Partial Cooling vs. Recompression sCO_2 Cycles

- **Study applies the CFB cost model to a recompression cycle and a partial cooling cycle, which has:**
  - Increased specific power due to higher sCO_2 cycle pressure ratio
  - Reduced cycle mass flow and recuperation duty
  - Reduced sCO_2 inlet temperature to primary heater
- **Approach:**
  - Incorporate primary heater pressure drop and cost
  - With and without reheat
  - Perform integrated COE optimization of primary heater and sCO_2 cycle



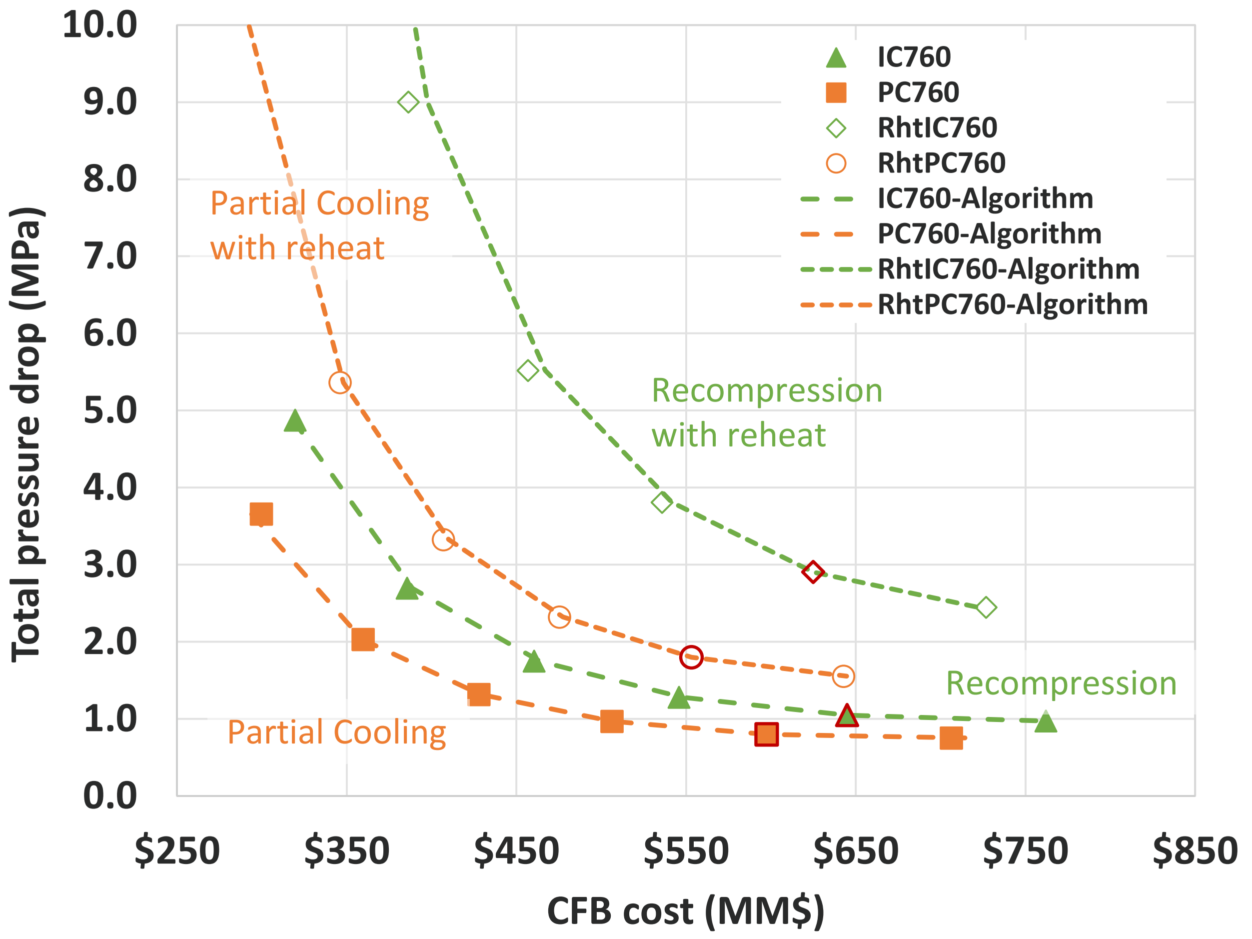
Cycle Parameter	Recomp -ression	Partial Cooling
Thermal Input (MW_{th})	1018	1056
Net Power Output (MW_e)	550	550
Cycle Efficiency	54.1	52.1
Specific Power (kJ/kg)	174	215
Mass Flow (kg/s)	3154	2558
Recuperation (MW_{th})	1923	1268
PHX Inlet Temp (°C)	509	438



CFB Pressure Drop vs Cost Results

Evaluated for a 760 °C Turbine Inlet Temperature

- **Partial cooling cycle without reheat (PC760) offers lowest CFB cost for same CFB pressure drop**
  - Followed by IC760, RhtPC760, RhtIC760
- **Reheat section pressure drops are significant**
  - Flow arrangement (heat recovery) should be carefully considered for reheat cases
- **CFB pressure drop vs. cost data will next be used to minimize the plant COE**



NETL's sCO_2 Techno-Economic Analyses

Past, Present, and Future Analyses

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Preliminary commercial-scale sCO_2 techno-economic analyses:**
  - Oxy-coal CFB indirect sCO_2 plant with carbon capture & storage (CCS) – 2017
  - Air-fired coal CFB indirect sCO_2 plant *without* CCS – 2019
  - Coal gasification integrated with direct sCO_2 plant with CCS – 2018
  - Natural gas-fueled direct sCO_2 plant with CCS – 2019
- **Detailed focus area studies for sCO_2 plant cost and efficiency improvements:**
  - sCO_2 component cost scaling study – ASME Turbo Expo 2019 (GT2019-90493)
  - sCO_2 cooling system cost and performance models – beta-testing ongoing
  - sCO_2 cooling system integration study – 3rd European sCO_2 Conference, 2019
  - sCO_2 heat source integration study (indirect sCO_2) – ongoing
  - Air separation unit modeling and integration (direct sCO_2) – ongoing
  - Direct sCO_2 turbine modeling – ongoing
  - Direct sCO_2 integration with alternative gasifiers – beginning Apr. 2020
- **Exemplar coal-fueled indirect sCO_2 plants, with and without CCS – June 2020**
- **Exemplar coal and natural gas direct sCO_2 plants with CCS – June 2021**
- **Techno-economic analysis of a NGCC plant with a sCO_2 bottoming cycle – Sept. 2020**

NATIONAL ENERGY TECHNOLOGY LABORATORY

Questions?

Nathan.Weiland@netl.doe.gov
Office: 412-386-4649

Acknowledgements:
KeyLogic: Chuck White, Sandeep Pidaparti, Drew O'Connell, Can Uysal
NETL: Wally Shelton, Travis Shultz, Eric Liese, Rich Dennis

NETL's sCO_2 Techno-Economic Analyses

Finding our research

- On www.OSTI.gov:
  - Search for: Subject = sCO2 AND Research Org = NETL
- On www.netl.doe.gov:
  - Go to:
    Research and Programs >
    Energy Analysis >
    Search Energy Analysis
  - Link to Website
  - Search: Collection Name = Supercritical CO2 (SCO2)