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sCO_2 Power Cycle Component Cost Correlations from DOE Data Spanning Multiple Scales and Applications

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Introduction

- **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
  - 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**

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 is maintained when exchanging quotes across each DOE laboratory, and in reporting results – no vendor data points are shared**
  - Only information needed for correlation development was shared (e.g., cost breakdown, temperature, pressures, pressure drop)
- **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**
  - All equipment costs are baselined to 2017 U.S. dollars using CEPCI index[1]

[1] S. Jenkins, "CEPCI Updates: January 2018 (Prelim.) and December 2017 (Final)," Chemical Engineering, 19 March 2018. [Online]. Available: https://www.chemengonline.com/cepci-updates-january-2018-prelim-and-december-2017-final/?printmode=1. [Accessed 10 September 2018]..

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
- **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]
  - CR value of 5 roughly corresponds to as-purchased or off-the-shelf prices
  - Vendor quotes with CR value of 1 are not sCO_2 specific, and not used for this study
- **Quote Confidence Ratings are used in the curve-fitting procedure and uncertainty quantification**
  - Lends statistical confidence to curve fits in which no vendor data points are shown

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.

Description of New Cost Algorithms

Methodology – Confidence-Weighted Correlations

- **Curve fitting procedure minimizes CR-weighted average absolute error between the actual quotes and the cost algorithms**
  - This procedure skews the correlation towards quotes with higher quality and confidence ratings
- **Uncertainty associated with the cost algorithm has two independent sources of error**
  - Uncertainty associated with vendor quote – Taken into account via confidence rating (U_{CR})
  - Cost algorithm weighted correlation error (how well the model fits the vendor data)

$$Error = \frac{\sum \left| \frac{Cost_{actual,i} - Cost_{model,i}}{Cost_{actual,i}} \right| CR_i}{\sum CR_i}$$

$$Uncertainty\ (U) = \sqrt{U_{CR}^2 + Error^2}$$

Components with New Cost Algorithms

Component	Number of Quotes	Ave. Confidence Rating
Coal-fired heaters	4	4.0
Natural gas-fired heaters	10	3.0
Recuperators	24	3.1
Direct air coolers	11	4.0
IG centrifugal compressors	15	2.7
Barrel type compressors	4	2.0
Axial turbines	6	3.7
Radial turbines	4	4.0
Motors	model	4.0
Generators	8	4.0
Gearboxes	7	4.1

Primary Heater Cost Algorithms

Inverted Tower Pulverized Coal Heaters and Natural Gas Fired Heaters

- **Inverted tower pulverized coal heaters:**
  - Thermal duty, Q selected as the scaling parameter
  - Better accuracy if overall conductance, UA selected as the scaling parameter
  - Includes: burners, fans, air preheaters, ductwork, headers, and interconnecting piping
  - Valid for: $T_{max} \leq 730$ °C and $26 \leq P \leq 31$ MPa
- **Natural gas-fired heaters:**
  - Thermal duty, Q selected as the scaling parameter
  - Includes: burners, emission controls, and air preheaters
  - Valid for: $T_{max} \leq 715$ °C and $23 \leq P \leq 27.5$ MPa

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

$$f_T = \begin{cases} 1 & \textbf{\textit{if}}\ T_{max} < 550\ ^\circ C \\ 1 + d(T_{max} - 550)^2 & \textbf{\textit{if}}\ T_{max} \geq 550\ ^\circ C \end{cases}$$

Component	Coal-fired heaters		Natural gas-fired heaters
Number of Quotes	4		10
Ave. Confidence Rating	4.0		3.0
Scaling Parameter, *SP*	Heat Duty	UA	Heat Duty
Units	MW_{th}	W/K	MW_{th}
SP Coefficient: *a*	820,800	1,248	632,900
SP Exponent: *b*	0.7327	0.8071	0.6
T^2 Coefficient: *d*	5.40E-5	5.30E-6	5.40E-5
Range: Low	187	7.40E+5	10
Range: High	1,450	5.90E+6	50
Uncertainty: Low	-23%	-16%	-25%
Uncertainty: High	26%	21%	33%
Installation Cost: Materials	0%		8%
Installation Cost: Labor	50%		12%

Recuperator Cost Algorithm

- **Cost algorithm based on 24 vendor quotes for HTRs and LTRs**
  - Includes PCHE, microtube, and plate-fin heat exchanger types (majority of the quotes are PCHE type)
- **Overall conductance, UA selected as the scaling parameter for curve fitting**
  - $UA = Q/\Delta T_{lm}$ calculation based on 1-D recuperator temperature modeling with 20 nodes
  - UA errors up to 80% for LTRs if endpoint temperature formulas are used
- **Valid for:**
  - $5 \leq Q \leq 3{,}000$ MW_{th}
  - $T_{max} < 585$ °C
  - $0.7 \leq \Delta P \leq 4$ bar
  - $21 \leq P \leq 32$ MPa

Component	Recuperators
Number of Quotes	24
Ave. Confidence Rating	3.1
Scaling Parameter, *SP*	UA
Units	W/K
SP Coefficient: *a*	49.45
SP Exponent: *b*	0.7544
T Coefficient: *c*	0.02141
SP Range: Low	1.60E+5
SP Range: High	2.15E+8
Uncertainty: Low	-31%
Uncertainty: High	38%
Installation Cost: Materials	2%
Installation Cost: Labor	3%

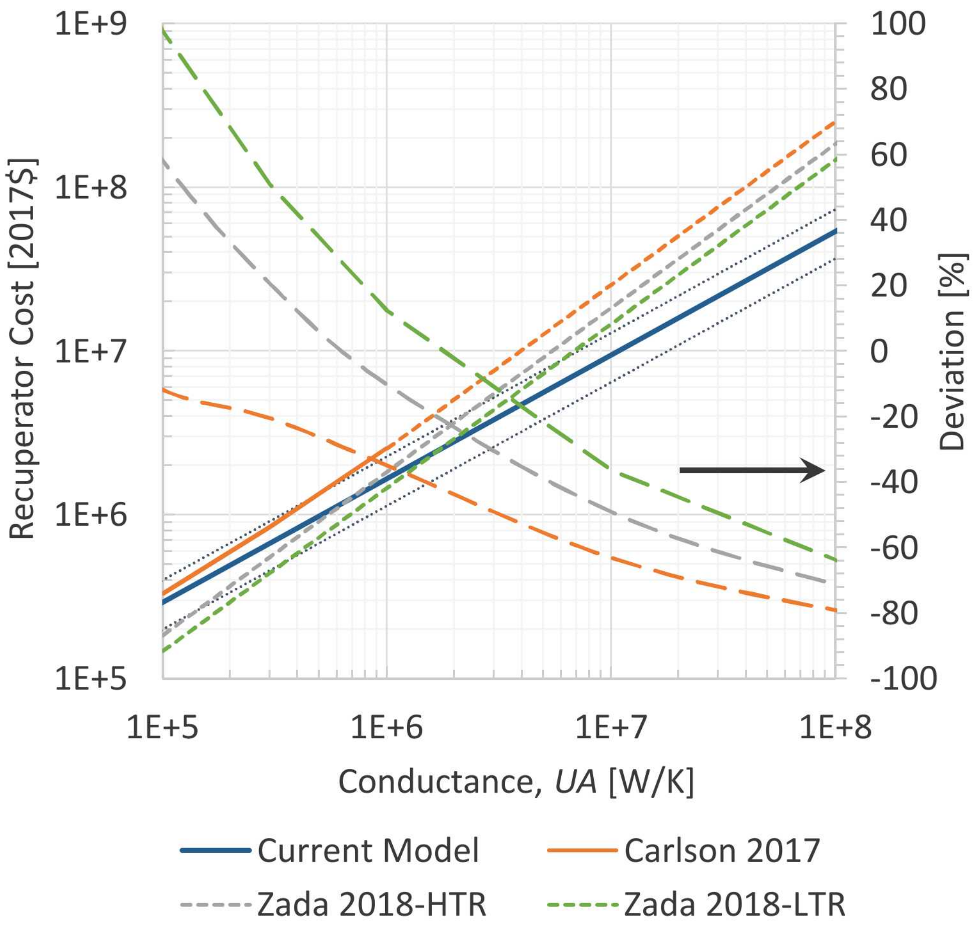
$$C = 49.45\ UA^{0.7544} \text{x}\ f_T$$

$$f_T = \begin{cases} 1 & \textbf{\textit{if}}\ T_{max} < 550\ ^{\circ}C \\ 1 + 0.02141(T_{max} - 550\ ^{\circ}C) & \textbf{\textit{if}}\ T_{max} \geq 550\ ^{\circ}C \end{cases}$$

Recuperator Cost Algorithm

Comparison with Existing Correlations

- **Developed cost algorithm is compared to models from literature**
  - Carlson et al.[3] and Zada et al.[4] models
  - Both these models are based on linear scaling with respect to UA
  - T_{max} set to 488 °C
- **New cost algorithm is consistent with:**
  - Carlson model for UA < 10^6 W/K
  - Zada model for UA ~ 10^6 W/K
- **Industry feedback indicated that the developed model**
  - Is able to capture the flattening of the cost curve for higher values of UA (> 10^6 W/K)
  - Over predicts cost for small scale heat exchangers (UA < 10^6 W/K)



[3] 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", 2017

[4] Kyle R. Zada, Ryan Kim, Aaron Wildberger, and Carl P. Schalansky. "Analysis of Supercritical CO_2 Brayton Cycle Heat Exchanger Size and Capital Cost with Variation of Layout Design", 2018

Direct Air Cooler Cost Algorithm

Direct Dry sCO_2 Coolers

- **Overall conductance, UA selected as the scaling parameter**
  - Overall conductance, UA is a function of the sCO_2 conditions, ambient air conditions and bay geometrical parameters such as number of tube rows, tube passes etc.
  - UA is calculated using discretized approach for crossflow heat exchangers[5]
- **Valid for:**
  - $25 \leq Q \leq 575$ MW_{th}
  - $T_{max} < 170$ °C
  - $5 \leq T_{amb} \leq 35$ °C
  - $0.5 \leq \Delta P \leq 1.5$ bar
  - $5.4 \leq P \leq 10$ MPa

Component	Direct air coolers
Number of Quotes	11
Ave. Confidence Rating	4.0
Scaling Parameter, *SP*	UA
Units	W/K
SP Coefficient: *a*	32.88
SP Exponent: *b*	0.75
SP Range: Low	8.60E+5
SP Range: High	7.50E+7
Uncertainty: Low	-25%
Uncertainty: High	28%
Installation Cost: Materials	8%
Installation Cost: Labor	12%

$$C = 32.88\, UA^{0.75}$$

[5] H. A. Navarro and L. C. Cabezas-Gómez, "Effectiveness-NTU computation with a mathematical model for cross-flow heat exchangers," *Brazilian Journal of Chemical Engineering*, vol. 24, no. 4, pp. 509-521, 2007.

Compressor Cost Algorithms

Integrally Geared and Barrel Type Centrifugal Compressors

- **Motor or turbine driver costs are calculated using separate algorithms, and are excluded in these models**
- **Integrally geared centrifugal compressors:**
  - Shaft power, $\dot{W}_{sh}$ selected as the scaling parameter
  - Valid for: $1.5 \leq \dot{W}_{sh} \leq 200 \text{MW}_{sh}$, $6.5 \leq P_{in} \leq 9$ MPa and $24.5 \leq P_{out} \leq 34.5$ MPa
- **Barrel type centrifugal compressors:**
  - Inlet volumetric flow, $\dot{V}_{in}$ selected as the scaling parameter
  - Valid for: $0.1 \leq \dot{V}_{in} \leq 2.4$ m^3/s, $7.6 \leq P_{in} \leq 8.2$ MPa and $21 \leq P_{out} \leq 25$ MPa

$$C = a\,SP^b$$

Component	Integrally geared compressors	Barrel type compressors
Number of Quotes	15	4
Ave. Confidence Rating	2.7	2.0
Scaling Parameter, *SP*	Shaft Power	Volumetric Flow
Units	MW_{sh}	m^3/s
SP Coefficient: *a*	1,230,000	6,220,000
SP Exponent: *b*	0.3992	0.1114
SP Range: Low	1.5	0.1
SP Range: High	200	2.4
Uncertainty: Low	-40%	-30%
Uncertainty: High	48%	50%
Installation Cost: Materials	8%	8%
Installation Cost: Labor	12%	12%

Turbine Cost Algorithms

Axial and Radial Turbines

- **Generator and gearbox costs have been subtracted from turbine quotes based on separate cost algorithms**
- **Axial Turbines:**
  - Shaft power, $\dot{W}_{sh}$ selected as the scaling parameter
  - Valid for: 10 ≤ $\dot{W}_{sh}$ ≤ 750 MW_{sh}, T_{max} < 730 °C and 24 ≤ P_{in} ≤ 28 MPa
- **Radial Turbines:**
  - Shaft power, $\dot{W}_{sh}$ selected as the scaling parameter
  - Valid for: 8 ≤ $\dot{W}_{sh}$ ≤ 35 MW_{sh}, T_{max} < 700 °C and 20 ≤ P_{in} ≤ 26 MPa

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

$$f_T = \begin{cases} 1 & \mathbf{if}\ T_{max} < 550\ ^\circ C \\ 1 + d(T_{max} - 550)^2 & \mathbf{if}\ T_{max} \geq 550\ ^\circ C \end{cases}$$

Component	Axial turbines	Radial turbines
Number of Quotes	6	4
Ave. Confidence Rating	3.7	4.0
Scaling Parameter, *SP*	Shaft Power	Shaft Power
Units	MW_{sh}	MW_{sh}
SP Coefficient: *a*	182,600	406,200
SP Exponent: *b*	0.5561	0.8
T^2 Coefficient: *d*	1.11E-4	1.14E-5
SP Range: Low	10	8
SP Range: High	750	35
Uncertainty: Low	-25%	-32%
Uncertainty: High	30%	51%
Installation Cost: Materials	8%	8%
Installation Cost: Labor	12%	12%

Other Turbomachinery Cost Algorithms

Motors, Generators, and Gearboxes

- **Motors:**
  - Derived for three different motor types using data from Aspen Process Economic Analyzer
  - Scaled with motor power, $\dot{W}_e$
- **Generators:**
  - Scaled with electric power output, $\dot{W}_e$
  - Valid for $4 \leq \dot{W}_e \leq 750$ MW_e (4-pole at small scales and 2-pole at large scales)
- **Gearboxes:**
  - Needed for turbine power < 65 MW_e
  - Scaled with shaft power, $\dot{W}_{sh}$
  - Valid for $4 \leq \dot{W}_{sh} \leq 10$ MW_{sh} and 25,000 ≤ Shaft speed ≤ 29,000 RPM

$$Cost = a\,SP^b$$

Component	Gearboxes	Generators	Explosion proof motors	Synchronous motors	Open drip-proof motors
Number of Quotes	7	8	model	model	model
Ave. Confidence Rating	4.1	4.0	4.0	4.0	4.0
Scaling Parameter, *SP*	Shaft Power	Electric Power	Electric Power	Electric Power	Electric Power
Units	MW_{sh}	MW_e	MW_e	MW_e	MW_e
SP Coefficient: *a*	177,200	108,900	131,400	211,400	399,400
SP Exponent: *b*	0.2434	0.5463	0.5611	0.6227	0.6062
SP Range: Low	4	4	0.00075	0.15	0.00075
SP Range: High	10	750	2.8	15	37
Uncertainty: Low	-15%	-19%	-15%	-15%	-15%
Uncertainty: High	20%	23%	20%	20%	20%
Installation Cost: Materials	8%	8%	8%	8%	8%
Installation Cost: Labor	12%	12%	12%	12%	12%

Summary of Cost Algorithms

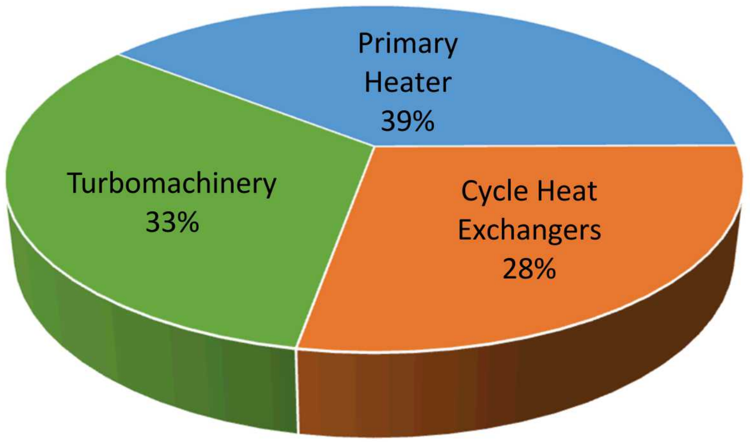
$$C = a\, SP^b \text{ x } f_T \qquad f_T = \begin{cases} 1 & \textbf{\textit{if}}\ T_{max} < 550\ ^\circ C \\ 1 + c(T_{max} - T_{bp}) + d(T_{max} - T_{bp})^2 & \textbf{\textit{if}}\ T_{max} \geq 550\ ^\circ C \end{cases}$$

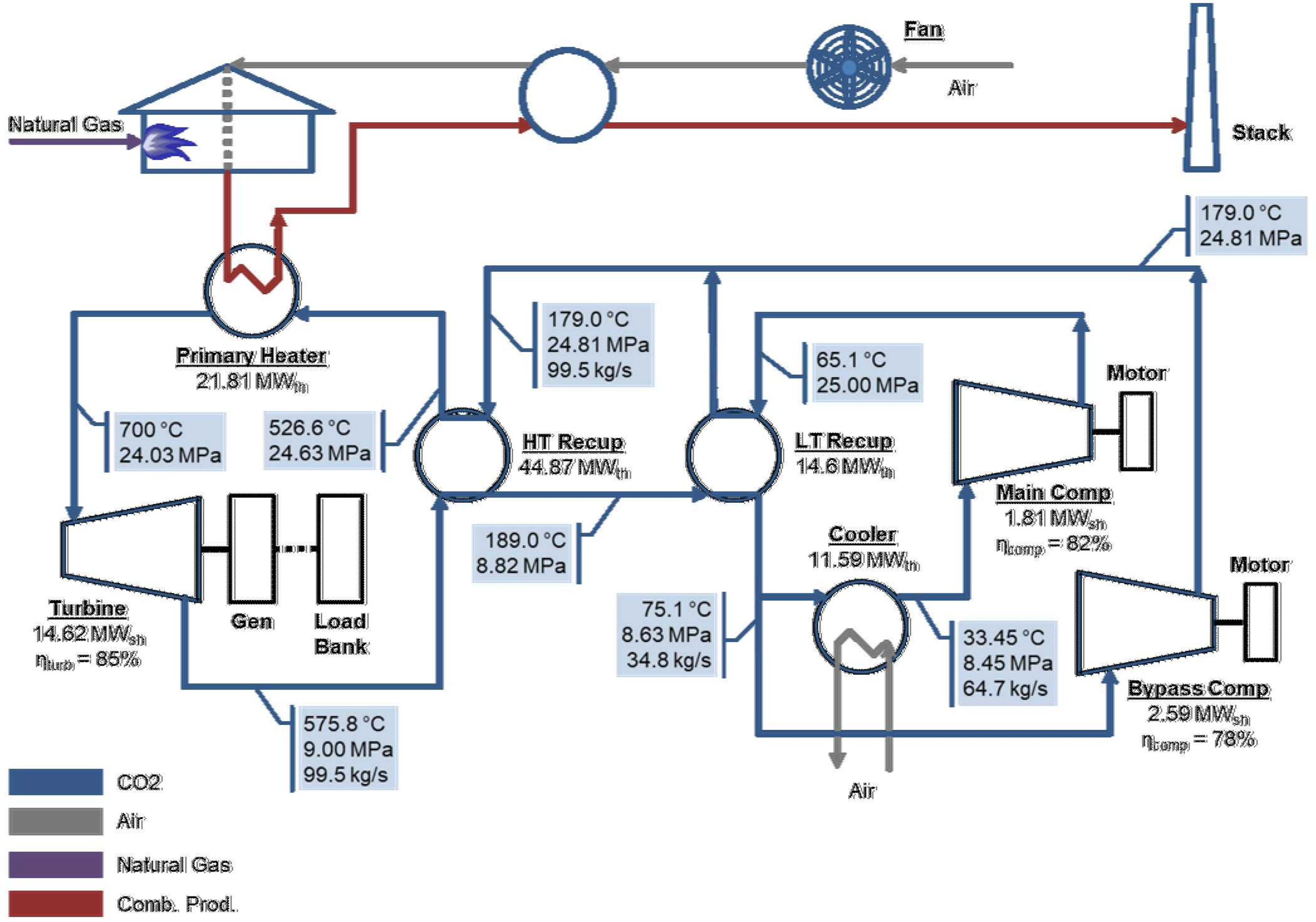
Component	Scaling Parameter (Units)	Coefficients				Database Range (Range of Validity)	Uncertainty Range
		a	b	c	d		
Coal-fired heaters	Q (MW_{th})	820,800	0.7327	0	5.4e-5	187 to 1,450 MW_{th}	-23% to +26%
Coal-fired heaters	UA (MW_{th})	1,248	0.8071	0	5.3e-6	7.4e5 to 5.9e6 W/K	-16% to +21%
Natural gas-fired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

Application of Cost Algorithms

Baseline 10 MW_e plant cost

- **Operating conditions for a 10 MW_e plant taken from Zitney & Liese[7]**
  - 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



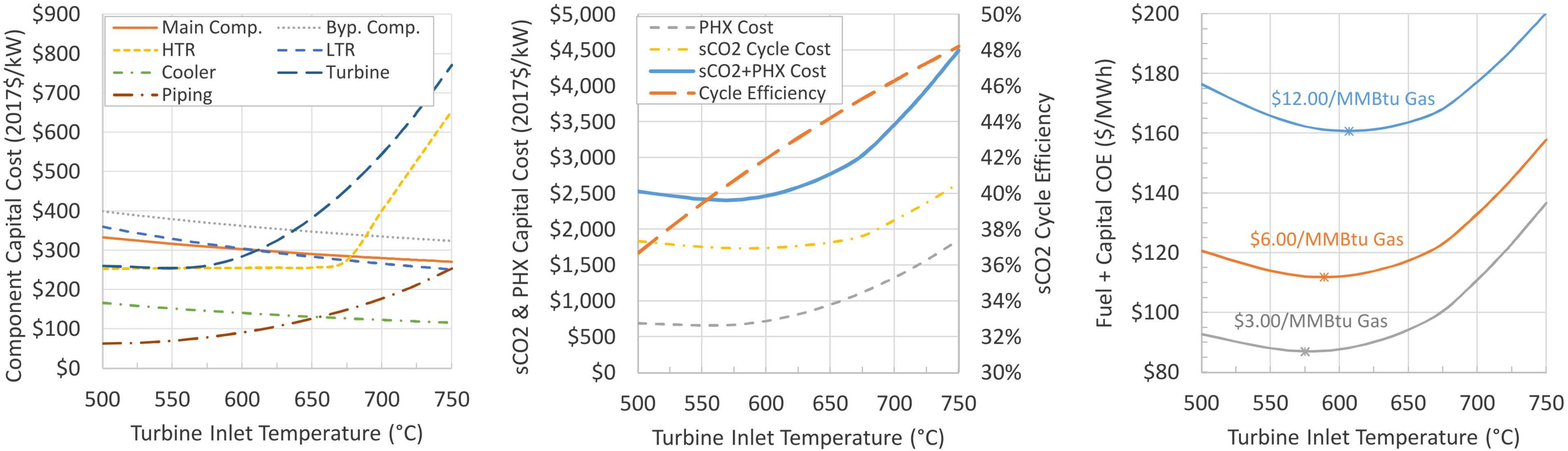


[7] S. E. Zitney and E. A. Liese, "Dynamic Modeling and Simulation of a 10 MWe Supercritical CO2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis," in The 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, 2018.

Application of Cost Algorithms

Sensitivity of 10 MW_e Plant to Turbine Inlet Temperature

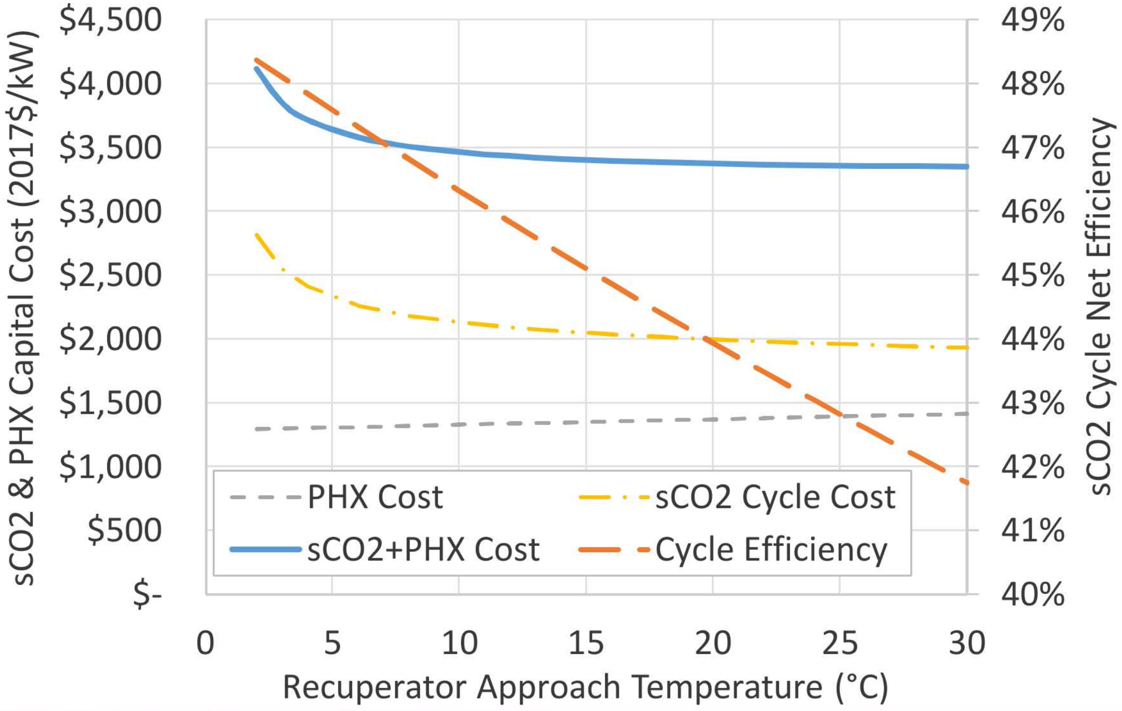
- **Using a spreadsheet cycle model developed with REFPROP, sensitivity analysis was conducted using the new cost algorithms (maintaining 10 MW_e net plant output)**
- **Optimized plant balances annualized capital cost against expected fuel cost**
- **Economics assume 80% capacity factor, 30 yr. plant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

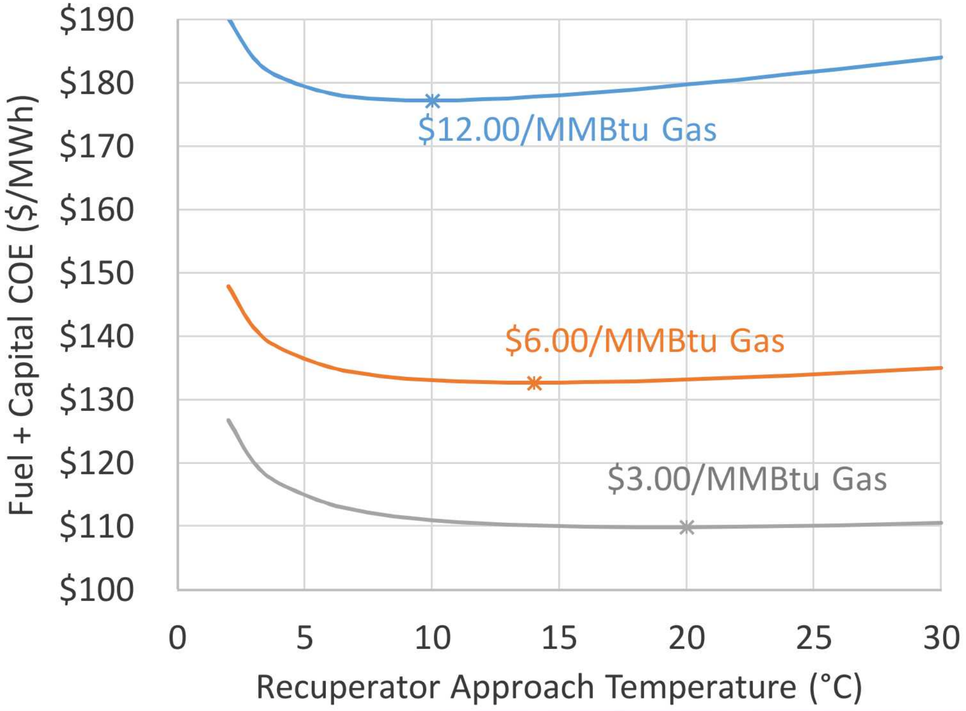


Application of Cost Algorithms

Sensitivity of 10 MW_e Plant to Recuperator Approach 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**





WNT1

Slide 22

LB12 Mostly curious, but is it easy to get the effectiveness value that relates to the optimal 20 C approach for $3 gas? With earlier cost models, I was finding that the optimal effectiveness was around 90%.

Lance, Blake, 6/10/2019

WNT1 For 20 C approach temp, I get an LTR effectiveness of 86.7%, and an HTR effectiveness of 94.7%

Weiland, Nathan T., 6/11/2019

Potential 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

Summary

- **Compilation of vendor quotes across multiple U.S. DOE National Laboratories has enabled collaborative development of detailed cost scaling relationships for sCO_2 components**
  - Developed cost algorithms span multiple sCO_2 applications (nuclear, fossil, solar) and size ranges (5-750 MW_e)
  - Temperature correction factors account for the cost increase associated with higher temperature material upgrades
  - Turbo-machinery costs are broken down to allow exploration of turbomachinery configurations cost implications
  - Uncertainties on the developed cost scaling relationships are quantified
  - Recommended installation cost factors are presented
- **Resulting cost correlations are reasonably accurate and comprehensive:**
  - Enables a shift from efficiency- to cost of electricity-based sCO_2 plant optimization
  - Ultimately results in accelerated commercialization of sCO_2 power cycles
- **So, let's see your cost-optimized sCO_2 plants!**

Questions?

Thank you for your time and attention!

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