Cooling System Cost & Performance Models for Economic sCO_2 Plant Optimization with Respect to Cold sCO_2 Temperature

Sandeep R. Pidaparti, Charles W. White, Andrew C. O'Connell, Nathan T. Weiland

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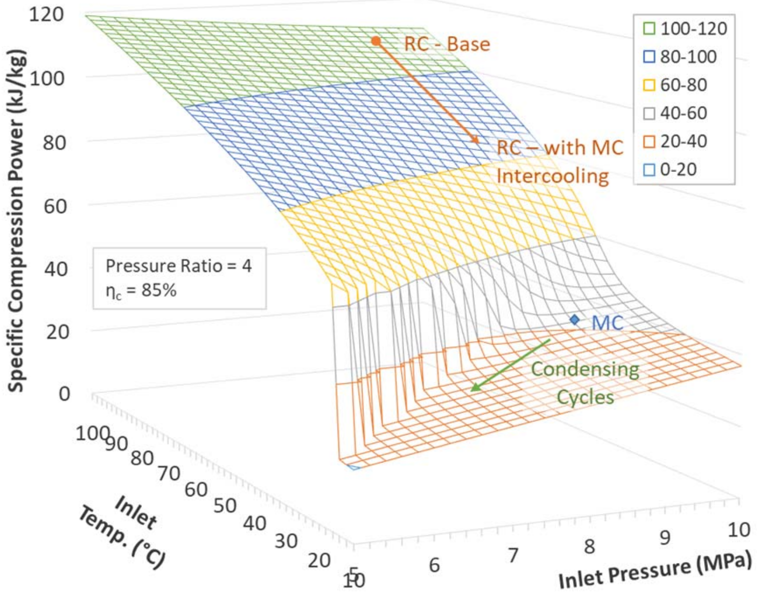
Cooling Systems for sCO_2 Power Cycles

Motivation

- **sCO_2 compression power requirements are very sensitive to the proximity of the operating condition to the CO_2 critical point**
  - Reducing CO_2 compressor inlet temperatures can significantly reduce compression power requirements
  - Improves sCO_2 cycle efficiency and specific power
- **Conventional cooling system design principles based on steam power cycles need to be reconsidered for sCO_2 power cycles**
  - Addition of low-cost cooling capacity can lower the compressor inlet temperature
  - Economic re-optimization of cooling system capacity and operating parameters



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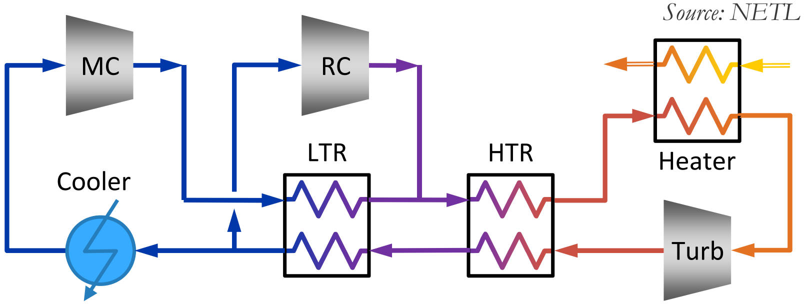

sCO_2 Cooling System Integration Study

- **Objective: Determine the extent to which increasing cooling capacity and optimizing cooling system operation conditions can improve the efficiency and cost of electricity (COE) for a utility-scale indirect sCO_2 power plant.**
- **Approach: Separate sCO_2 cycle and cooler system analyses**
  - Determine steady state plant performance as a function of cooler exit temperature and pressure, as well as the number of main compressor intercooling stages[1]
    - Novel options for resolution of resulting heat exchanger temperature pinch point problems
    - Quantify impact on plant efficiency, specific power and other cycle parameters
  - Develop spreadsheet cost and performance models of wet and dry cooling technologies, for direct and indirect CO_2 cooling
  - Optimize plant COE as a function of cooling technology, cooler design & capacity, and cold CO_2 temperature

Cooler type	Operation	
	Wet	Dry
Direct (sCO_2)	✓	✓
Indirect (water)	✓	✓

- **Expected Impacts**
  - Cooling system optimization results are applicable to all sCO_2 plant types
  - Published cooler cost and performance modeling tools will enable similar COE optimization by others
  - Enables COE optimization at any sCO_2 plant site given its ambient conditions

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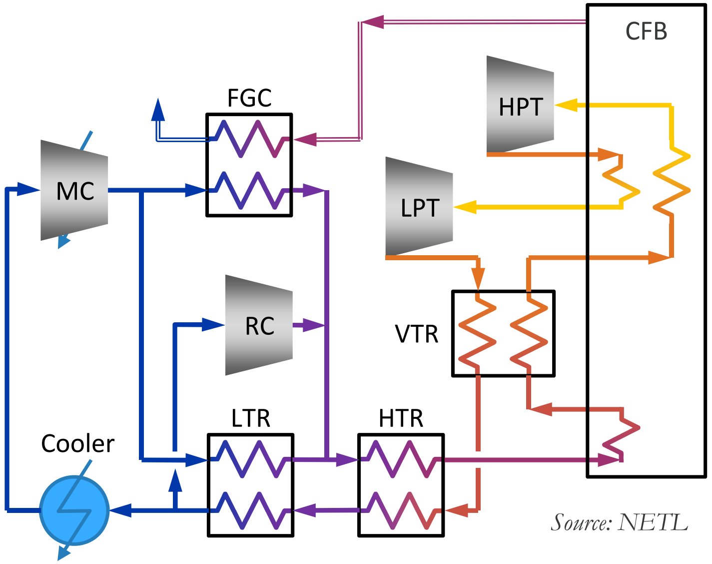
[1] Weiland, N.T., White, C.W., and O'Connell, A.C., "Effects of Cold Temperature and Main Compressor Intercooling on Recuperator and Recompression Cycle Performance," *2nd European Supercritical CO2 Conference*, Essen, Germany, August 30-31, 2018. NETL-PUB-21819

sCO_2 Recompression Brayton Cycle

General Plant Design and Assumptions

- **Ambient conditions: Midwestern U.S.**[2]
  - Average dry bulb temperature, T_{db}: 15 °C
  - Relative humidity: 60% (T_{wb} = 10.8 °C)
  - Ambient pressure: 1.01325 bars
- **Oxy-coal indirect sCO_2 plant model with carbon capture & storage used from prior work**[3]**:**
  - Circulating Fluidized Bed (CFB) oxy-coal combustor
  - Reheat turbine
  - Third recuperator (VTR) and an economizer after the HTR
  - Intercooled main CO_2 compressor
  - Flue gas cooler (FGC) in parallel with the LTR
- **Balance of plant (BOP) cooling needs (e.g., ASU compressor intercoolers, etc.) modeled with a dedicated wet cooling tower system**
  - Isolates influence of cold temperature to sCO_2 cycle

Parameter	Value
Turbine inlet temperature (°C)	760
Turbine exit pressure (MPa)	7.9
Compressor outlet pressure (MPa)	34.6
Nominal compressor pressure ratio	3.8
Turbine isentropic efficiency	0.927
Compressor isentropic efficiency	0.85
Cycle pressure drop (MPa)	0.41
Minimum temperature approach (°C)	5.6



Source: NETL

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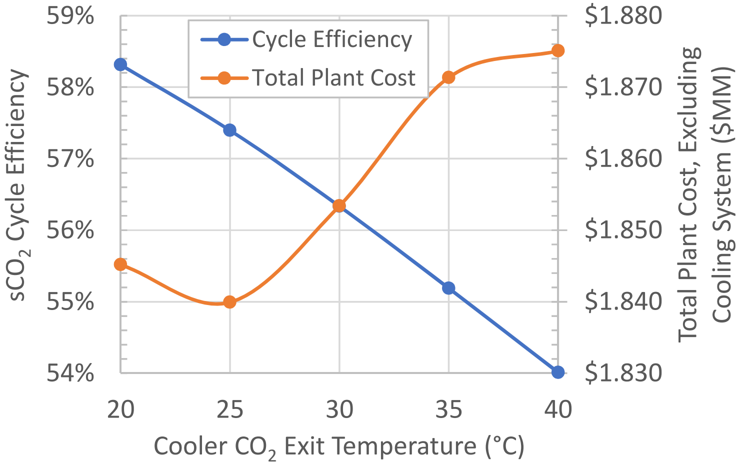
[2] National Energy Technology Laboratory (NETL), "Quality Guidelines for Energy System Studies: Process Modeling Design Parameters," NETL, Pittsburgh, May 2014.

[3] National Energy Technology Laboratory (NETL), "Techno-economic Evaluation of Utility-Scale Power Plants Based on the Indirect sCO2 Brayton Cycle," DOE/NETL- 2017/1836, Pittsburgh, PA, September 2017.

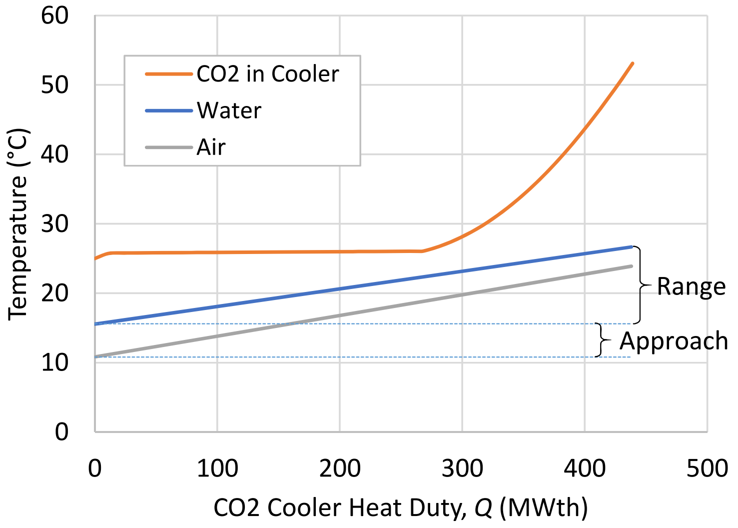
Approach to Evaluating Cooler Models

- **For ease of modeling, sCO_2 cycles were optimized separately from cooler systems for fixed sCO_2 cooler exit temperatures of 20, 25, 30, 35, & 40 °C**
  - Main compressor inlet pressure optimized for each temperature to maximize efficiency
  - Recuperator and cooler approach temperatures adjusted to avoid internal pinch points
- **Plant efficiency, total plant cost, and cost of electricity (COE) are the sum of:**
  - Cost and performance of optimized sCO_2 cycle and non-cooling auxiliary systems
  - Cooling system auxiliary loads and costs, determined using the cooling system spreadsheet models
  - Costs for circulating water treatment and ancillary systems scaled from cooling system water use
- **For a given plant design and ambient conditions, the goal is to identify:**
  - Optimal operating conditions for each cooling technology
  - Which cooling technology provides the lowest COE
  - The optimal cold sCO_2 temperature that minimizes the COE of the plant



Indirect vs. Direct Cooling Technologies

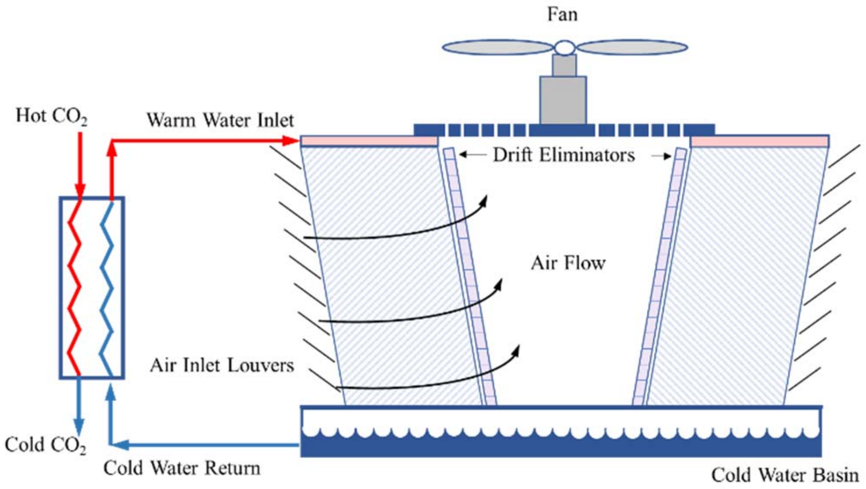
- **CO_2 cooling systems divided into two main categories:**
  - Systems that directly cool the CO_2 using ambient air (direct dry cooling and adiabatic cooling)
  - Systems that indirectly cool CO_2 with water as an intermediate (wet cooling towers and indirect dry cooling)
- **For indirectly-cooled sCO_2 plants, water/CO_2 heat exchangers are required:**
  - CO_2 inlet & outlet conditions are fixed by the sCO_2 cycle
  - Water inlet & outlet conditions set by cooler Range and Approach to ambient temperature design variables
  - Water/CO_2 heat exchanger design indirectly determined
    - Log Mean Temperature Difference ($LMTD$) calculated from a discretized 1-D counterflow heat exchanger model, with a check for internal temperature crosses
  - Water/CO_2 heat exchanger cost is assumed to be identical to a low temperature recuperator, which scales with $UA = Q/LMTD$



Wet Cooling Tower Technology

Performance and Cost Model

- **Performance model modified from an existing wet cooling model**[4]
  - Extended to calculate psychrometric properties based on ambient conditions
- **Zanker correlation for estimation of cooling tower installed cost**[5, 6]
  - Based on thermal duty, water range, approach temperature, and wet bulb temperature
  - Cost correlation doesn't account for the cooling water pumps, water piping, etc., which are calculated separately.



Input Parameters	Output Parameters
Cooling duty	Circulating water flow rate
Ambient dry bulb temperature	Circulating water pump power consumption
Ambient wet bulb temperature	Cooling tower water loss and make-up requirement
Ambient pressure	Cooling tower air flow rate
Cooling water range	Cooling tower fan power consumption
Water approach	Cooling tower construction cost

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[4] Baumeister, T., Avallone, E., and T. Baumeister III, *Marks' Standard Handbook for Mechanical Engineers, 8th Ed.*, McGraw-Hill, pp 9-72 – 9-73 (1979)

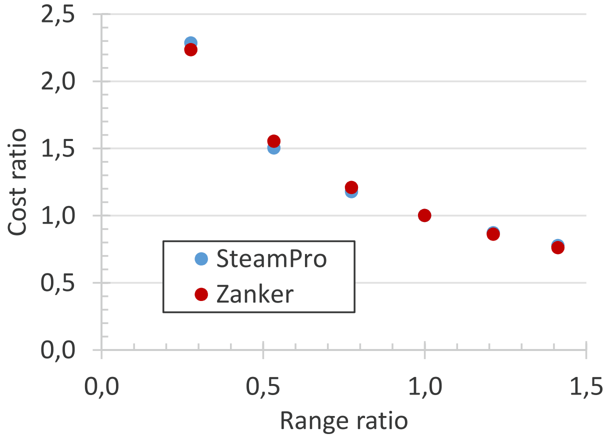
[5] Zanker, A., "Cooling Tower Costs from Operating Data," Calculation and Shortcut Handbook, McGraw-Hill,New York, pp 47-48 (1967)

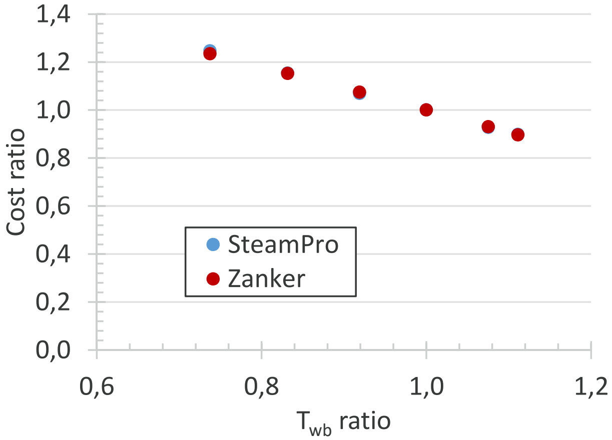
[6] Leeper, S. A., "Wet Cooling Tower: 'Rule-of-thumb' Design and Simulation," Idaho National Engineering Laboratory, EGG-GTH-5775, pp 10-11 (1981)

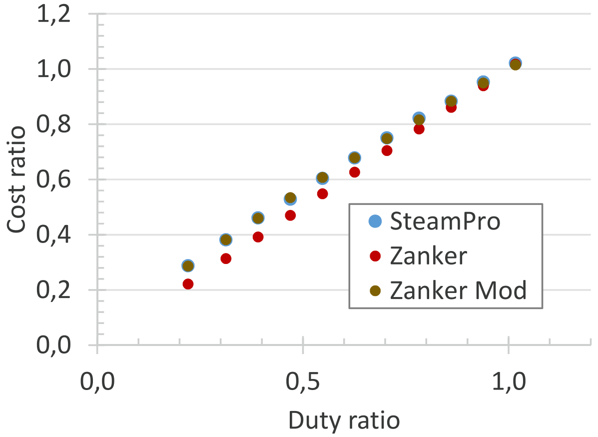
Wet Cooling Tower Technology

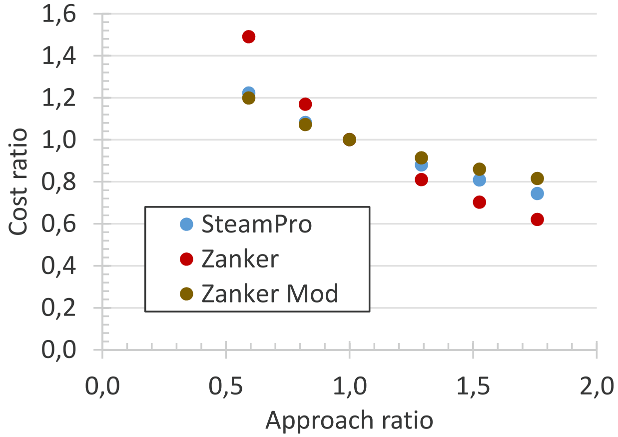
Cost Model Validation with SteamPro

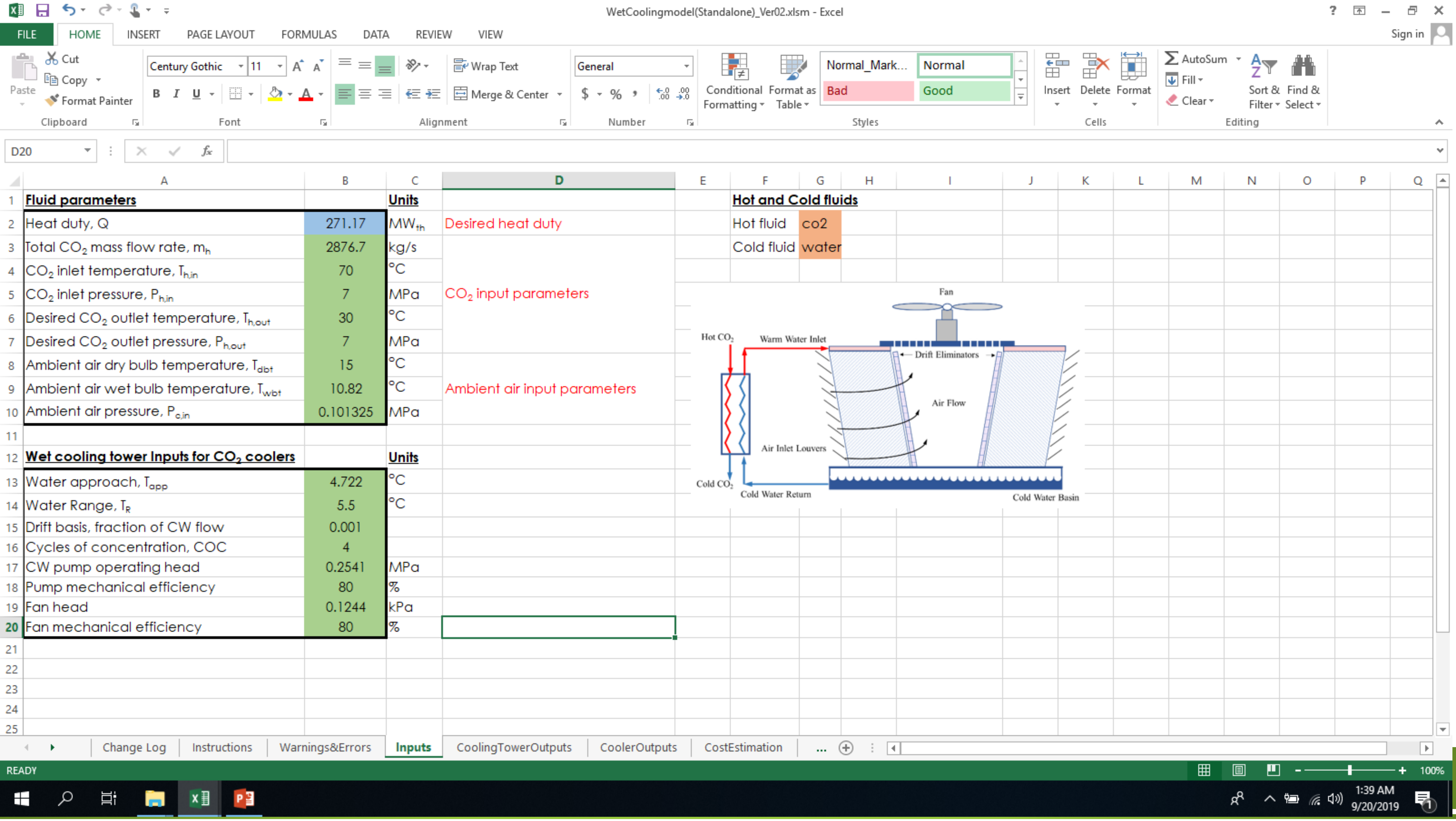
- **Cost model validated against cooling tower cost models from SteamPro**
  - Zanker correlation compared well with SteamPro data for variation of cooling water Range and wet bulb temperature, T_{wb}
  - Zanker correlation adjusted with power law exponents for cooling Duty and Approach temperature to yield a good fit
    - Denoted Zanker Mod
    - See paper for correlation





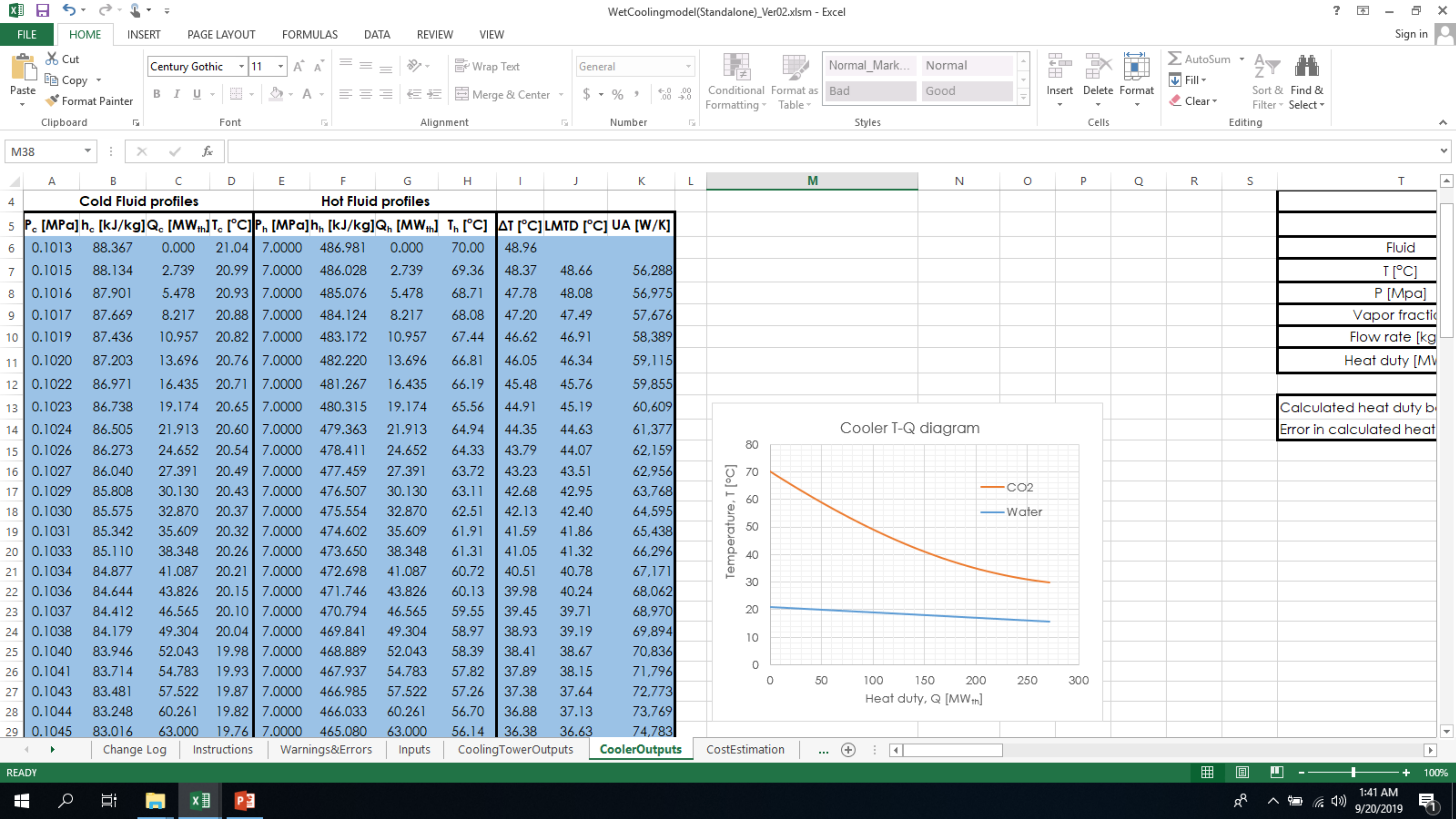






	A	B	C	D
1	**Fluid parameters**		**Units**	
2	Heat duty, Q	271.17	MW_{th}	Desired heat duty
3	Total CO_2 mass flow rate, m_h	2876.7	kg/s	
4	CO_2 inlet temperature, $T_{h,in}$	70	°C	
5	CO_2 inlet pressure, $P_{h,in}$	7	MPa	CO_2 input parameters
6	Desired CO_2 outlet temperature, $T_{h,out}$	30	°C	
7	Desired CO_2 outlet pressure, $P_{h,out}$	7	MPa	
8	Ambient air dry bulb temperature, T_{dbt}	15	°C	
9	Ambient air wet bulb temperature, T_{wbt}	10.82	°C	Ambient air input parameters
10	Ambient air pressure, $P_{c,in}$	0.101325	MPa	
11				
12	**Wet cooling tower Inputs for CO_2 coolers**		**Units**	
13	Water approach, T_{app}	4.722	°C	
14	Water Range, T_R	5.5	°C	
15	Drift basis, fraction of CW flow	0.001		
16	Cycles of concentration, COC	4		
17	CW pump operating head	0.2541	MPa	
18	Pump mechanical efficiency	80	%	
19	Fan head	0.1244	kPa	
20	Fan mechanical efficiency	80	%	

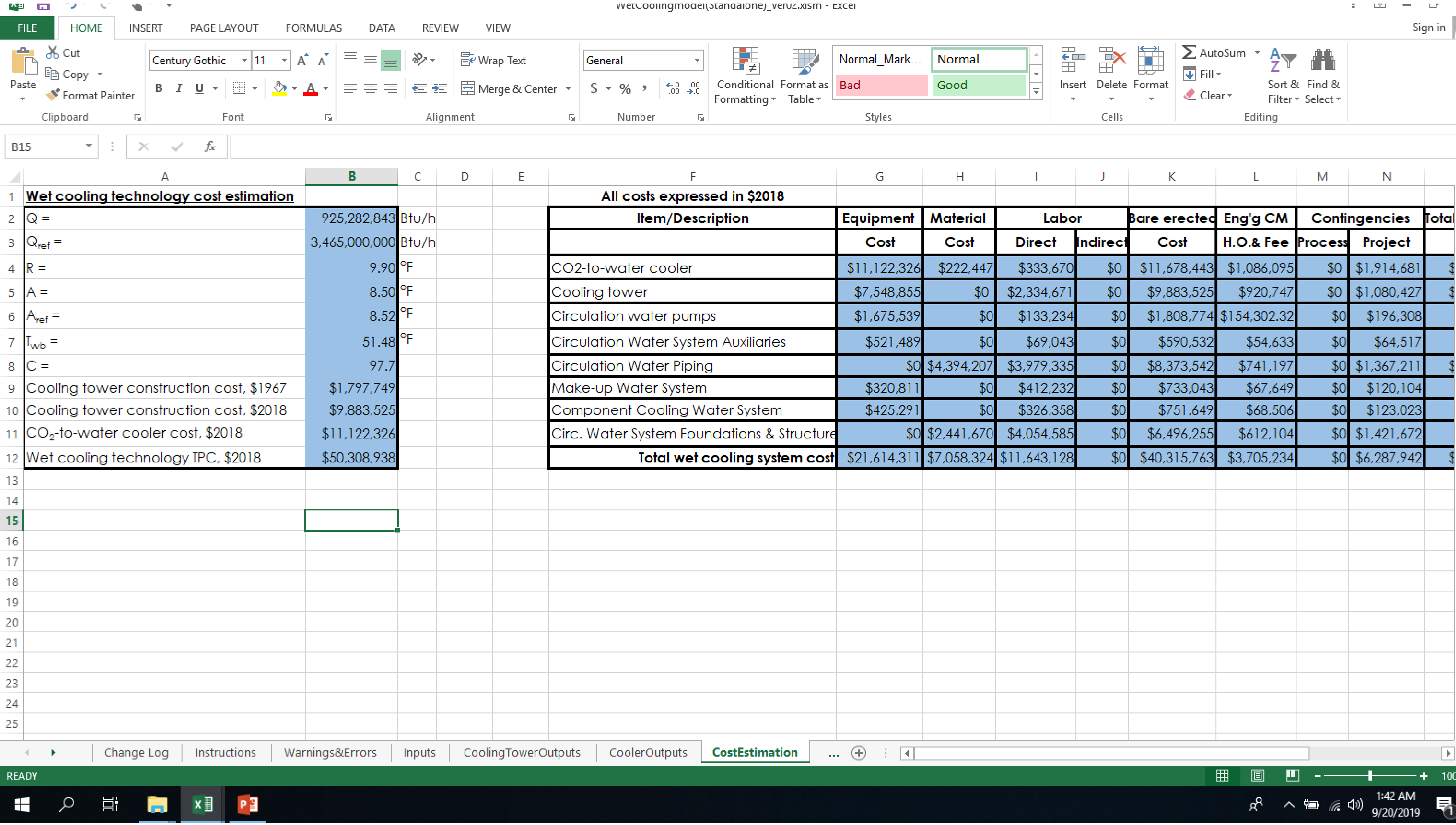
F	G
Hot and Cold fluids	
Hot fluid	co2
Cold fluid	water



Cold Fluid profiles				Hot Fluid profiles						
P_c [MPa]	h_c [kJ/kg]	Q_c [MW$_{th}$]	T_c [°C]	P_h [MPa]	h_h [kJ/kg]	Q_h [MW$_{th}$]	T_h [°C]	ΔT [°C]	LMTD [°C]	UA [W/K]
0.1013	88.367	0.000	21.04	7.0000	486.981	0.000	70.00	48.96		
0.1015	88.134	2.739	20.99	7.0000	486.028	2.739	69.36	48.37	48.66	56,288
0.1016	87.901	5.478	20.93	7.0000	485.076	5.478	68.71	47.78	48.08	56,975
0.1017	87.669	8.217	20.88	7.0000	484.124	8.217	68.08	47.20	47.49	57,676
0.1019	87.436	10.957	20.82	7.0000	483.172	10.957	67.44	46.62	46.91	58,389
0.1020	87.203	13.696	20.76	7.0000	482.220	13.696	66.81	46.05	46.34	59,115
0.1022	86.971	16.435	20.71	7.0000	481.267	16.435	66.19	45.48	45.76	59,855
0.1023	86.738	19.174	20.65	7.0000	480.315	19.174	65.56	44.91	45.19	60,609
0.1024	86.505	21.913	20.60	7.0000	479.363	21.913	64.94	44.35	44.63	61,377
0.1026	86.273	24.652	20.54	7.0000	478.411	24.652	64.33	43.79	44.07	62,159
0.1027	86.040	27.391	20.49	7.0000	477.459	27.391	63.72	43.23	43.51	62,956
0.1029	85.808	30.130	20.43	7.0000	476.507	30.130	63.11	42.68	42.95	63,768
0.1030	85.575	32.870	20.37	7.0000	475.554	32.870	62.51	42.13	42.40	64,595
0.1031	85.342	35.609	20.32	7.0000	474.602	35.609	61.91	41.59	41.86	65,438
0.1033	85.110	38.348	20.26	7.0000	473.650	38.348	61.31	41.05	41.32	66,296
0.1034	84.877	41.087	20.21	7.0000	472.698	41.087	60.72	40.51	40.78	67,171
0.1036	84.644	43.826	20.15	7.0000	471.746	43.826	60.13	39.98	40.24	68,062
0.1037	84.412	46.565	20.10	7.0000	470.794	46.565	59.55	39.45	39.71	68,970
0.1038	84.179	49.304	20.04	7.0000	469.841	49.304	58.97	38.93	39.19	69,894
0.1040	83.946	52.043	19.98	7.0000	468.889	52.043	58.39	38.41	38.67	70,836
0.1041	83.714	54.783	19.93	7.0000	467.937	54.783	57.82	37.89	38.15	71,796
0.1043	83.481	57.522	19.87	7.0000	466.985	57.522	57.26	37.38	37.64	72,773
0.1044	83.248	60.261	19.82	7.0000	466.033	60.261	56.70	36.88	37.13	73,769
0.1045	83.016	63.000	19.76	7.0000	465.080	63.000	56.14	36.38	36.63	74,783

Fluid
T [°C]
P [Mpa]
Vapor fracti
Flow rate [kg
Heat duty [MW

Calculated heat duty b
Error in calculated heat



Wet cooling technology cost estimation

Q =	925,282,843	Btu/h
Q_{ref} =	3,465,000,000	Btu/h
R =	9.90	°F
A =	8.50	°F
A_{ref} =	8.52	°F
T_{wb} =	51.48	°F
C =	97.7	
Cooling tower construction cost, $1967	$1,797,749	
Cooling tower construction cost, $2018	$9,883,525	
CO_2-to-water cooler cost, $2018	$11,122,326	
Wet cooling technology TPC, $2018	$50,308,938	

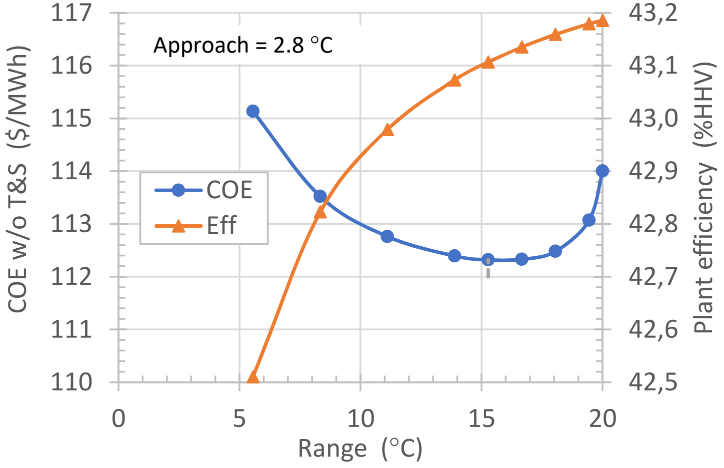
All costs expressed in $2018

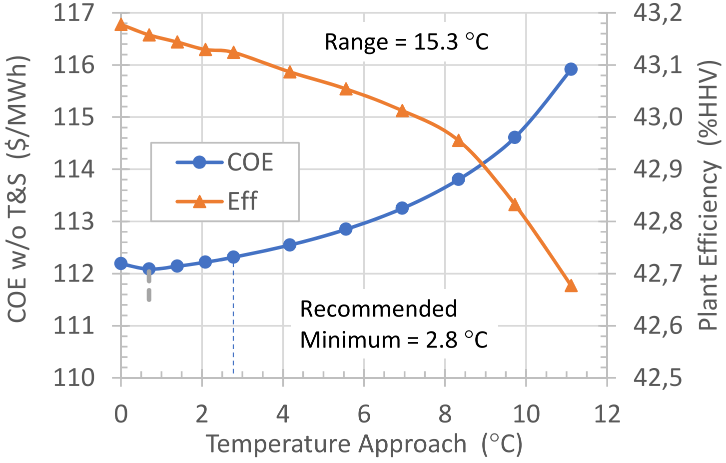
Item/Description	Equipment	Material	Labor		Bare erected	Eng'g CM	Contingencies		Total
	Cost	Cost	Direct	Indirect	Cost	H.O.& Fee	Process	Project	
CO2-to-water cooler	$11,122,326	$222,447	$333,670	$0	$11,678,443	$1,086,095	$0	$1,914,681	$
Cooling tower	$7,548,855	$0	$2,334,671	$0	$9,883,525	$920,747	$0	$1,080,427	$
Circulation water pumps	$1,675,539	$0	$133,234	$0	$1,808,774	$154,302.32	$0	$196,308	
Circulation Water System Auxiliaries	$521,489	$0	$69,043	$0	$590,532	$54,633	$0	$64,517	
Circulation Water Piping	$0	$4,394,207	$3,979,335	$0	$8,373,542	$741,197	$0	$1,367,211	$
Make-up Water System	$320,811	$0	$412,232	$0	$733,043	$67,649	$0	$120,104	
Component Cooling Water System	$425,291	$0	$326,358	$0	$751,649	$68,506	$0	$123,023	
Circ. Water System Foundations & Structure	$0	$2,441,670	$4,054,585	$0	$6,496,255	$612,104	$0	$1,421,672	
Total wet cooling system cost	$21,614,311	$7,058,324	$11,643,128	$0	$40,315,763	$3,705,234	$0	$6,287,942	$

Wet Cooling Tower Results

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)

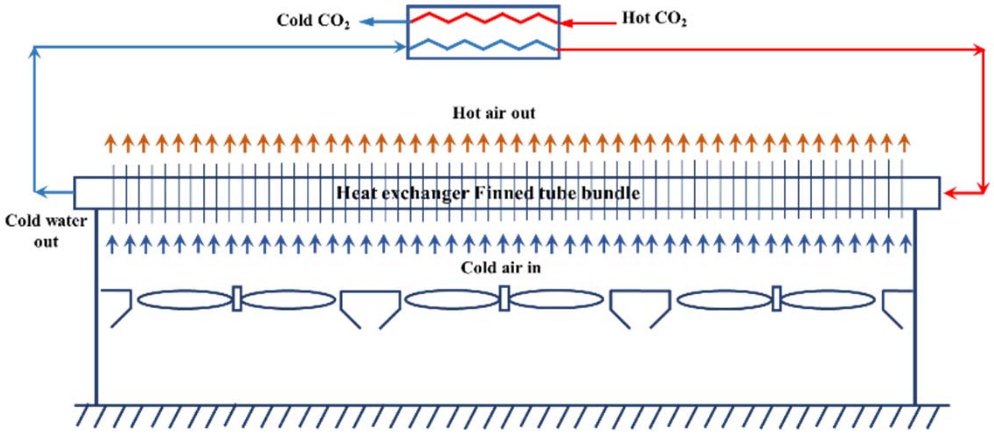




Indirect Dry Cooling Technology – ACHE

Performance Model

- **Performance model based on ACHE text[7] and calibrated with data from a vendor quote from Black & Veatch**
  - Assumes two tube passes in a crossflow heat exchanger arrangement
  - Required air flow and number of ACHE bays needed solved iteratively using *ε-NTU* relationships for crossflow heat exchangers
- **ACHE cost scaled linearly by number of bays required to meet cooling demand**



Inputs	Outputs
Cooling duty	Circulating water flow rate
Cooling water range	Air flow rate
Water temperature approach to T_{db}	Average air exit temperature
Ambient air-dry bulb temperature	Total fan power consumption
---	Number of bays needed
---	ACHE capital cost

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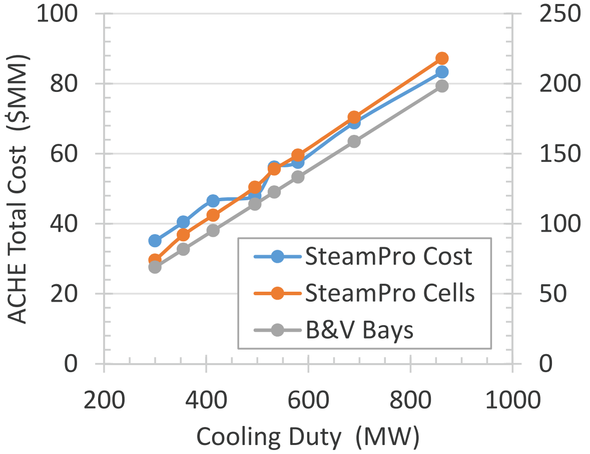
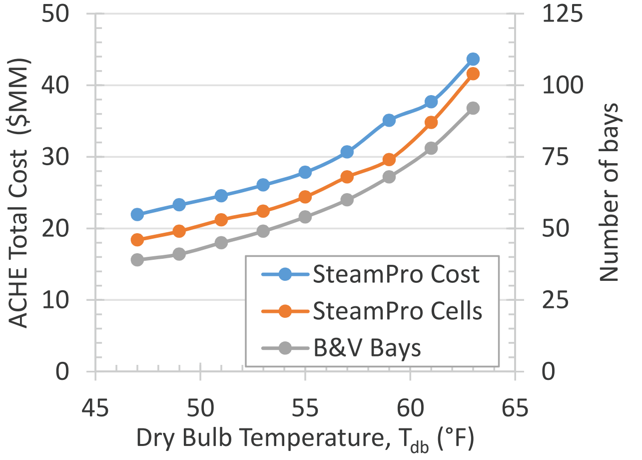
[7] Kroger, D. G., Air-cooled Heat Exchangers and Cooling Towers: Thermal Performance Evaluation and Design Volume II, PennWell Corp., Tulsa, OK, pp 134-153 (2004)

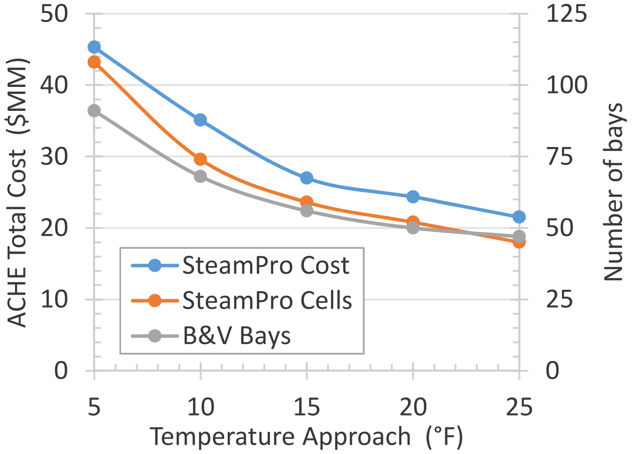
Indirect Dry Cooling Technology – ACHE

Cost Model Validation with SteamPro

- **Cost model validated against ACHE costs obtained from SteamPro**
  - Linear scaling of cooling duty with number of ACHE bays validated
  - Also validates linear scaling of cost with number of bays
- **Increasing design dry bulb temperature and reducing temperature approach to ambient requires more cooler bays**
- **Maximum cost deviation occurs for Approach < 5.6 °C (10 °F)**



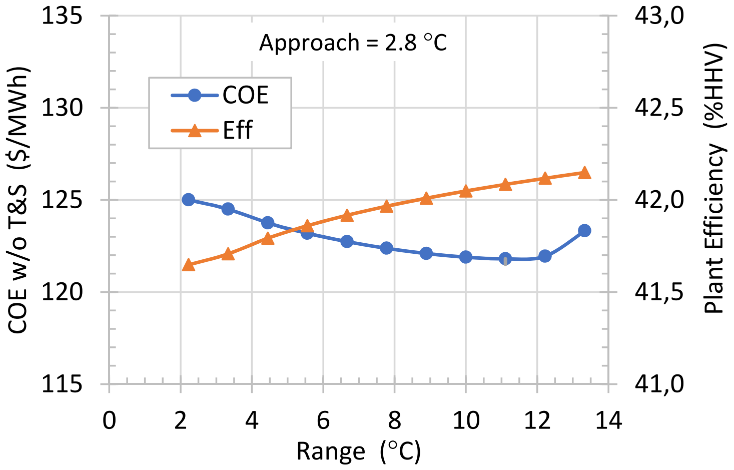


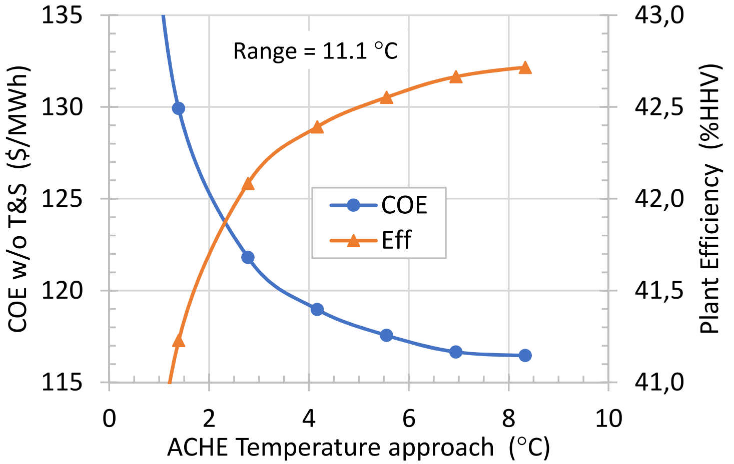


Indirect Dry Cooling Technology Results

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, while ACHE capital costs decrease
  - Opposing cost trends minimize the plant's COE for a cooling water range of 11.1 °C in this example case.
- **For increasing Temperature Approach:**
  - Fan power decreases, increasing efficiency
  - Smaller number of ACHE bays needed, but water/CO_2 heat exchanger costs also increase
  - Optimum temperature approach that minimizes COE is ≥ 8 °C in this example

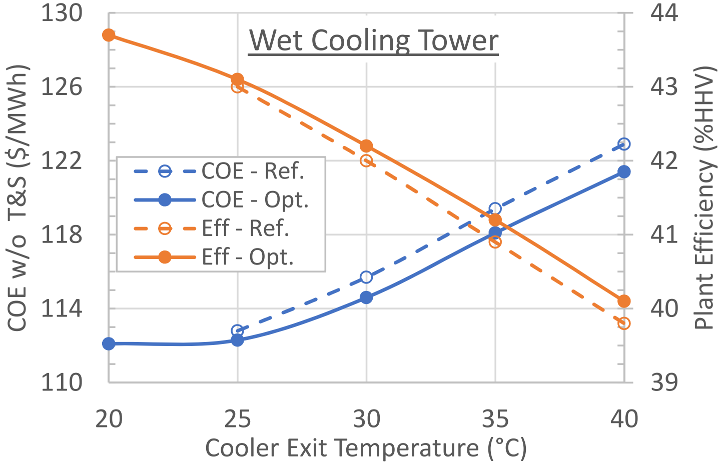


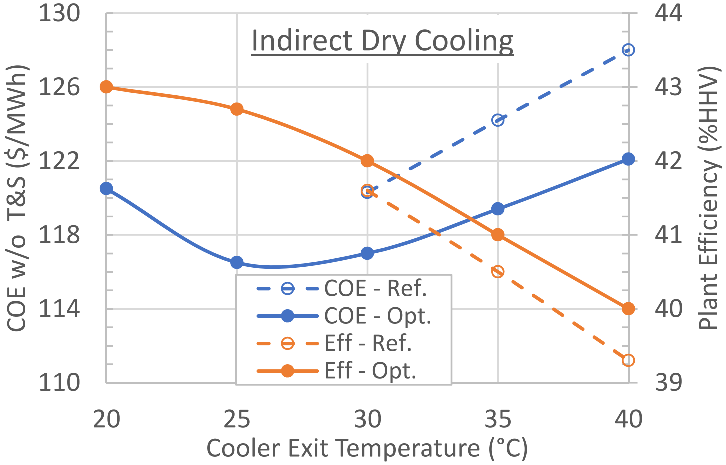


Indirect Cooling Technology Optimization

Operating Condition Optimization

- **Indirect sCO_2 cooling technologies can be optimized relative to reference cooling water assumptions typically used for steam power cycles[2]:**
  - Reference cooling water range: 11.1 °C (20 °F)
  - Reference cooling water approach to T_{wb}: 4.7 °C (8.5 °F)
- **Optimal wet cooling tower operating conditions for sCO_2 are not far from the reference cooling conditions used for steam**
- **Significant benefit to optimizing indirect dry cooling systems for sCO_2**
  - Also extends operation to colder sCO_2 temperatures
- **Optimum CO_2 cooler temperature will depend on the plant design (cooling technology cost fraction) and ambient conditions**





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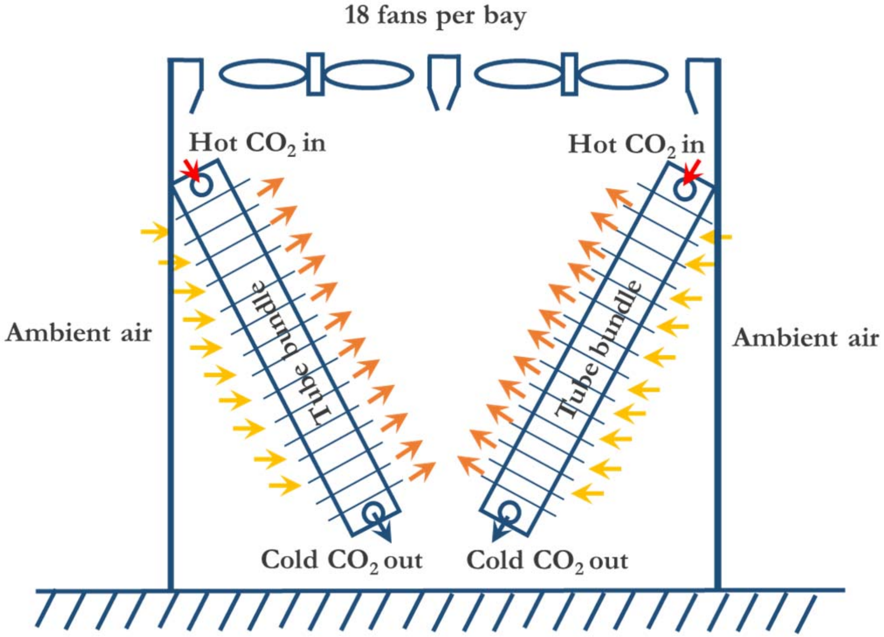
[2] National Energy Technology Laboratory (NETL), "Quality Guidelines for Energy System Studies: Process Modeling Design Parameters," NETL, Pittsburgh, May 2014.

Direct Dry Cooling Technology

Performance Model

- **Performance model based on ACHE Text[8] and calibrated with data from a vendor cost estimate from Guentner**
- **Iterative calculation of outputs using a discretized model of the crossflow heat exchanger tube bundle**
  - Effectiveness, ε of each sub-section is calculated using ε-*NTU* relationship for crossflow heat exchangers
  - Separate ε-*NTU* relationships are used for condensing and non-condensing scenarios
  - Includes heat transfer coefficient and pressure drop correlations for air and CO_2 sides
  - Incorporates fan scaling laws and fan test data from ACHE textbook[7]



Inputs	Outputs
Cooling duty	Average air exit temperature
CO_2 inlet temperature & pressure	Total fan power consumption
CO_2 outlet temperature	Number of bays needed
Ambient air-dry bulb temperature	Cooler capital cost
Air flow rate per bay	Performance of each cooler bay

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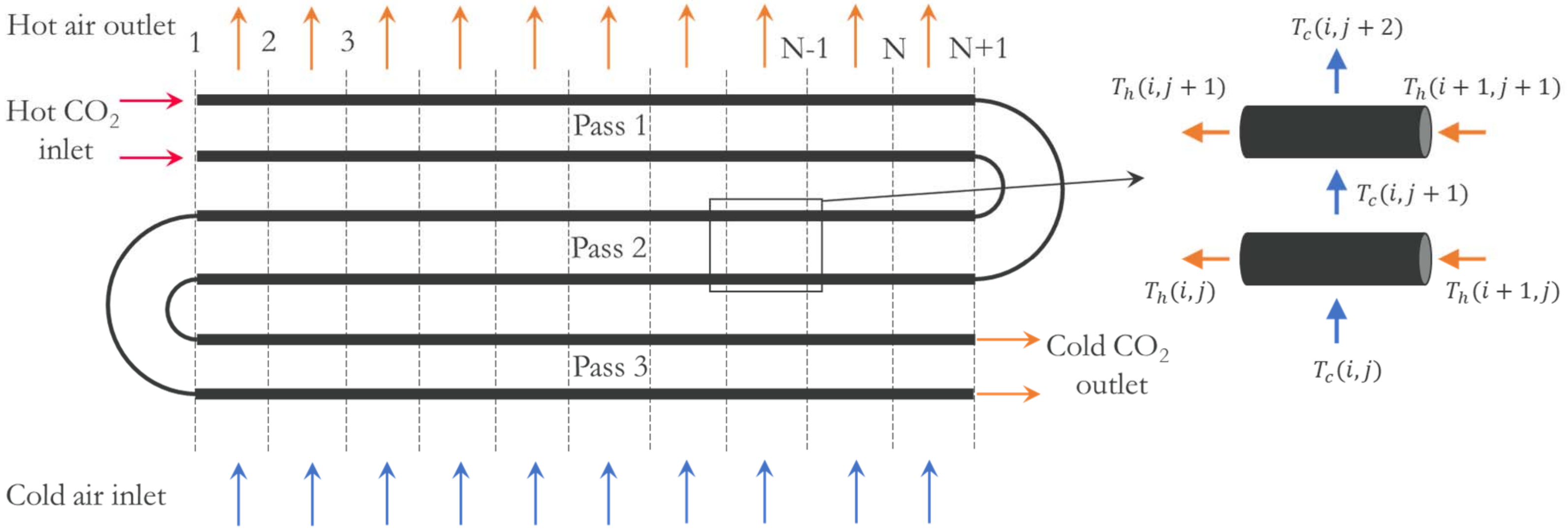
[7] Kroger, D. G., Air-cooled Heat Exchangers and Cooling Towers: Thermal Performance Evaluation and Design Volume II, PennWell Corp., Tulsa, OK, pp 134-153 (2004)

Direct Dry Cooling Technology

Discretization scheme & tube bundle description



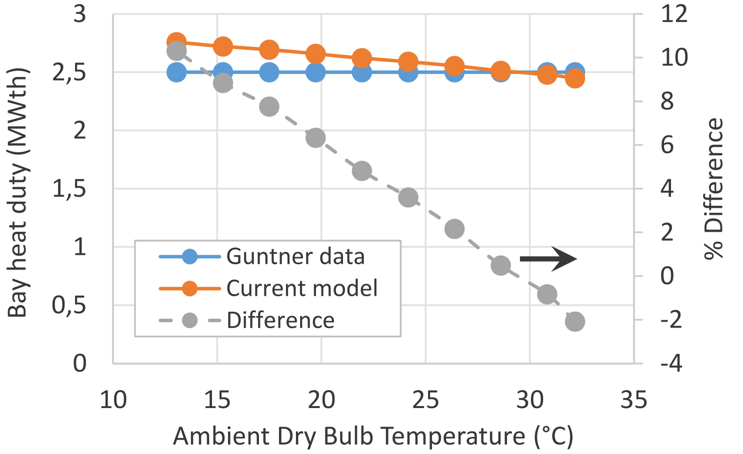
Parameter	Value
Tube outer diameter (mm)	12
Tube wall thickness (mm)	0.7
Tube inner diameter (mm)	10.6
Finned tube length (m)	11.385
Tube arrangement pattern	Staggered
Fin thickness (mm)	0.15
Number of tube bundles	2
Number of tubes per row	64
Number of tube passes	3
Number of tubes per pass	2

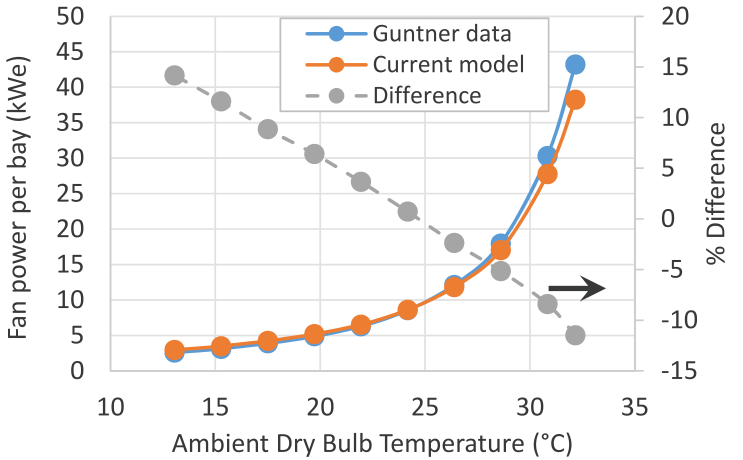
- **The cooler model discretization scheme includes multiple tube rows and passes**
  - Accounts for non-linear property variation near the critical point
- **Air side heat transfer coefficient and pressure drop correlations are tuned to match the vendor data**

Direct Dry Cooling Technology

Performance Model - Validation with Vendor data

- **Vendor calculated volumetric flow rate of air and fan power consumption as a function of the ambient dry bulb temperature for fixed number of bays and heat duty**
- **The volumetric flow rate is used as the input to the model to calculate heat duty, fan power consumption per bay**
- **The model is able to predict the vendor data for bay heat duty and fan power consumption within ±10% and ±15%, respectively.**
    - This accuracy is deemed acceptable, since the model doesn't fully replicate the vendor tube bundle or fan configuration

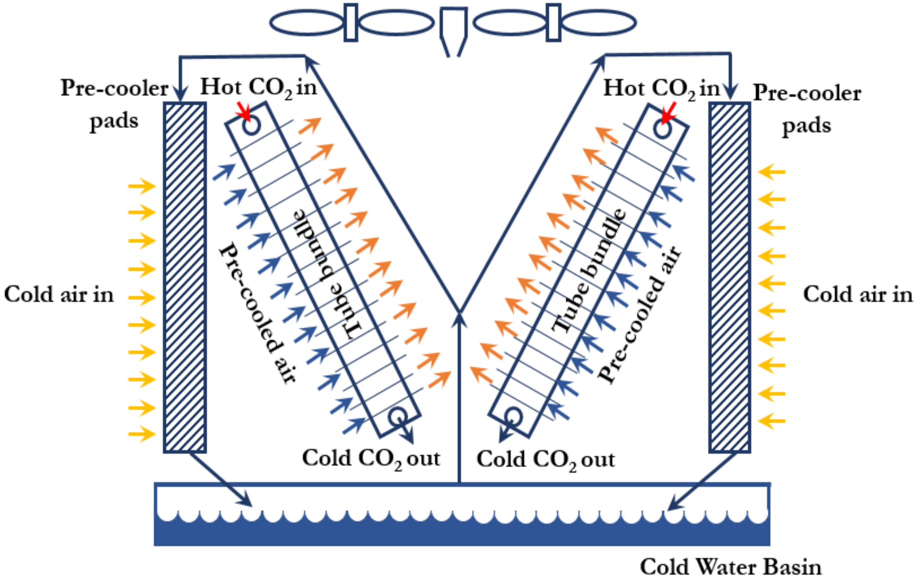




Direct Adiabatic Cooling Technology

Performance Model

- **"Adiabatic" cooler systems developed to improve CO_2-based refrigeration system performance during hot ambient conditions**
  - Addition of wet pre-cooling pads cools incoming air through evaporation
  - Allows for a CO_2 approach to the wet bulb, rather than dry bulb, temperature
  - Operator flexibility to utilize water pre-cooler pads only when needed
- **Wet pre-cooler pad model solves water and air mass & energy balances**
  - Pre-cooler model results are inputs to the direct dry cooling technology performance model
  - Model performance and cost calibrated to vendor data and quote

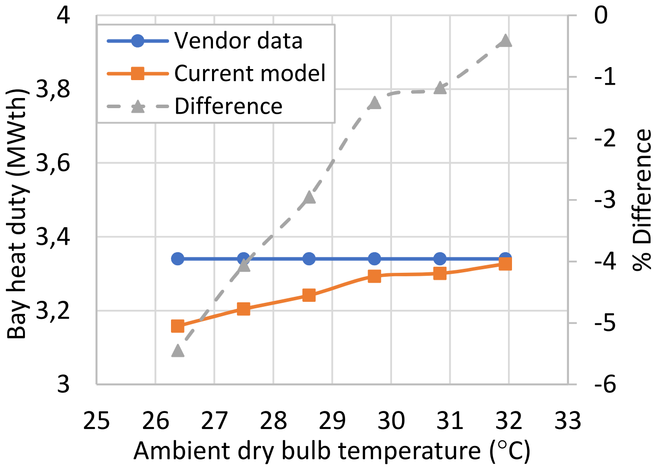


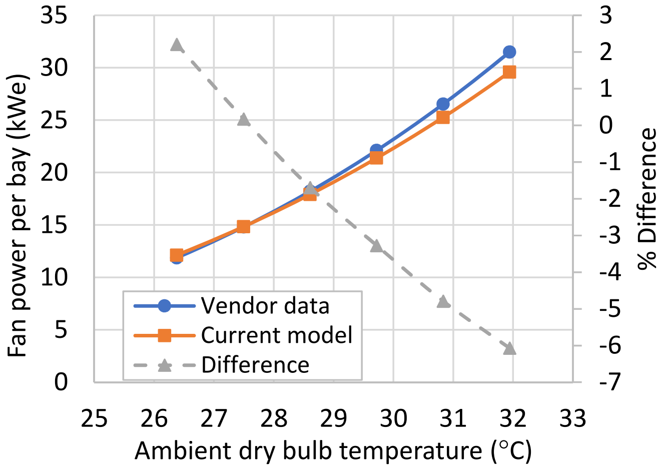
Inputs	Outputs
Cooling duty	Air temperature after cooling pad
CO_2 inlet temperature & pressure	Air temperature exiting cooler
CO_2 outlet temperature	Total fan power consumption
Ambient air dry bulb temperature	Water consumption rate
Ambient air wet bulb temperature	Number of bays needed
Air flow rate per bay	Cooler capital cost

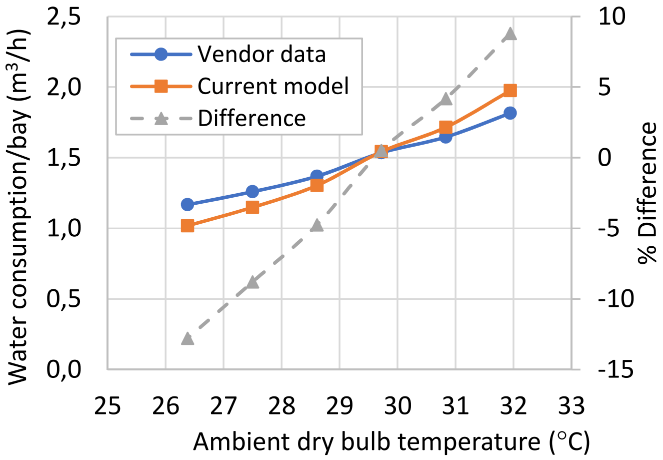
Direct Adiabatic Cooling Technology

Performance model - Validation with vendor data

- **For a fixed heat duty and number of bays, vendor calculated volumetric flow rate of air, fan power consumption, and water consumption rate as a function of the ambient dry and wet bulb temperatures**
  - Model calculations of fan power consumption, heat duty and water consumption rate compared well with vendor predictions for wide range of conditions (±10% agreement for most cases)
  - This accuracy is deemed acceptable, since the model doesn't fully replicate the vendor tube bundle, fan configuration, or wet pre-cooler pads



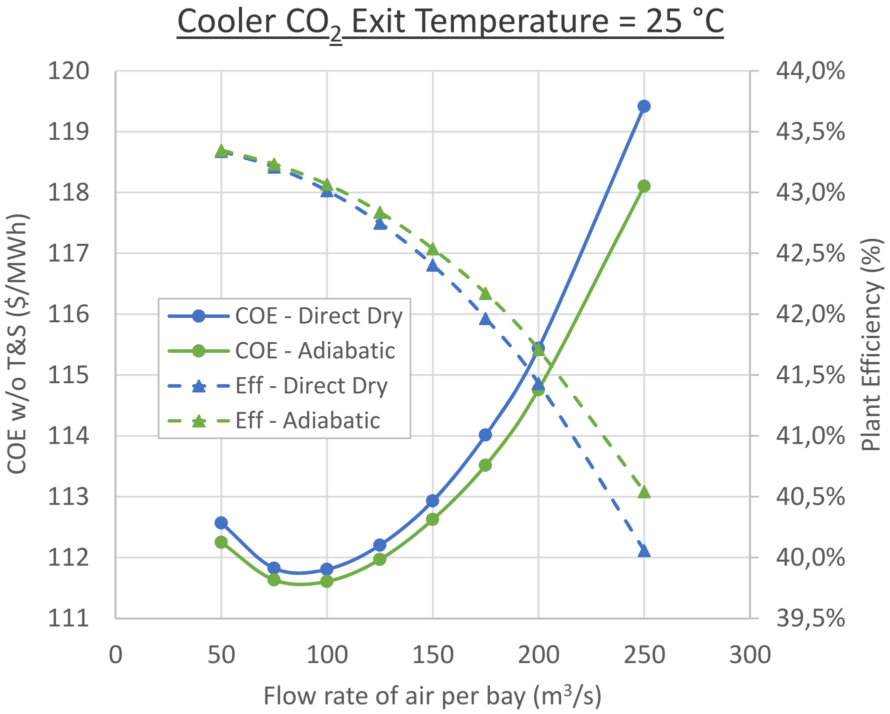




Direct Dry and Adiabatic Cooling Results

Efficiency and COE Sensitivity to Range and Approach

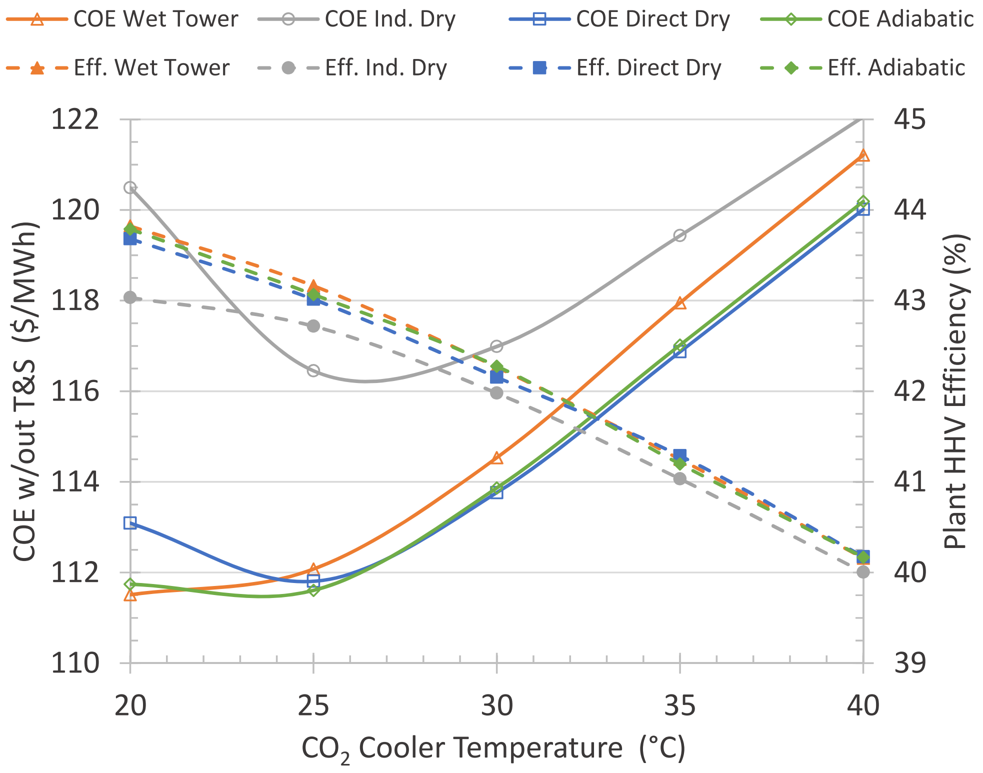
- **For increasing volumetric air flow rate:**
  - Efficiency decreases due to increasing fan power consumption
  - The number of required cooler bays decreases, resulting in lower CO_2 cooler capital costs
  - Due to these opposing trends, the COE attains a minimum value for a particular value of air flow rate (approximately 90 m^3/s in this example case).
- **Relative to the Direct Dry cooler, the Direct Adiabatic Cooler:**
  - Requires fewer bays to meet the cooling demand, reducing both cost and fan power consumption
  - Due to CO_2 approach to lower T_{wb}, rather than T_{db}



Cooling Technology Comparison

Efficiency and COE Optimization Results

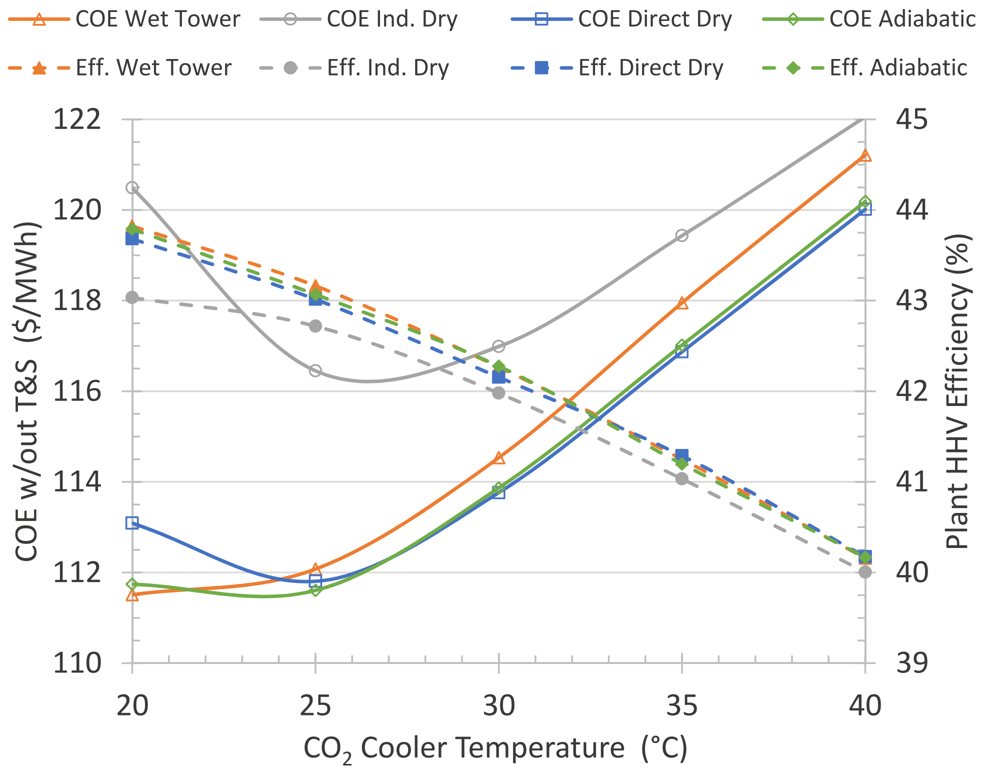
- **Cooler operating conditions optimized for COE at each cooler temperature**
  - Optimized results are valid only for the plant design and ambient conditions selected
- **CO_2 cooler exit temperatures of 20-25 °C minimize COE**
  - Demonstrates the benefit of condensing CO_2 cycle operation
- **Plant efficiency improves 3.0 – 3.5 percentage points, and the plant COE is reduced by as much as 8%, by decreasing the CO_2 cooler temperature from 40 to 20 °C, depending on the cooling technology**



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)



Summary and Future Work

- **Summary**
  - Developed four cooler cost and performance spreadsheet models for minimizing sCO_2 power plant COE by optimizing cold cycle temperature and cooling system operation
    - Models freely available for use (currently beta-test versions, attached to the models' technical documentation[8])
  - Improvements in plant efficiency (3.0–3.5 %points) and plant COE (up to 8%) highlight the importance of cooling system thermal integration and optimization of CO_2 cooler temperature for sCO_2 power plants
- **Current and Future Work**
  - Modification of cooler technology models to handle sCO_2 mixtures for optimizing direct sCO_2 power cycle cooling systems
  - Investigation of cooling system optimization for different plant sites and ambient conditions
  - Modification of cooling system models to predict off-design performance

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[8] National Energy Technology Laboratory (NETL), "Cooling Technology Performance and Cost Models for sCO2 Power Cycles," NETL, Pittsburgh, 2019. https://www.netl.doe.gov/energy-analysis/details?id=3199.

Questions?

nathan.weiland@netl.doe.gov