Cooling System Cost and Performance Models to Minimize Cost of Electricity of Direct sCO_2 Power Plants (Paper # 113)

NATIONAL ENERGY TECHNOLOGY LABORATORY

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NETL Support Contractor

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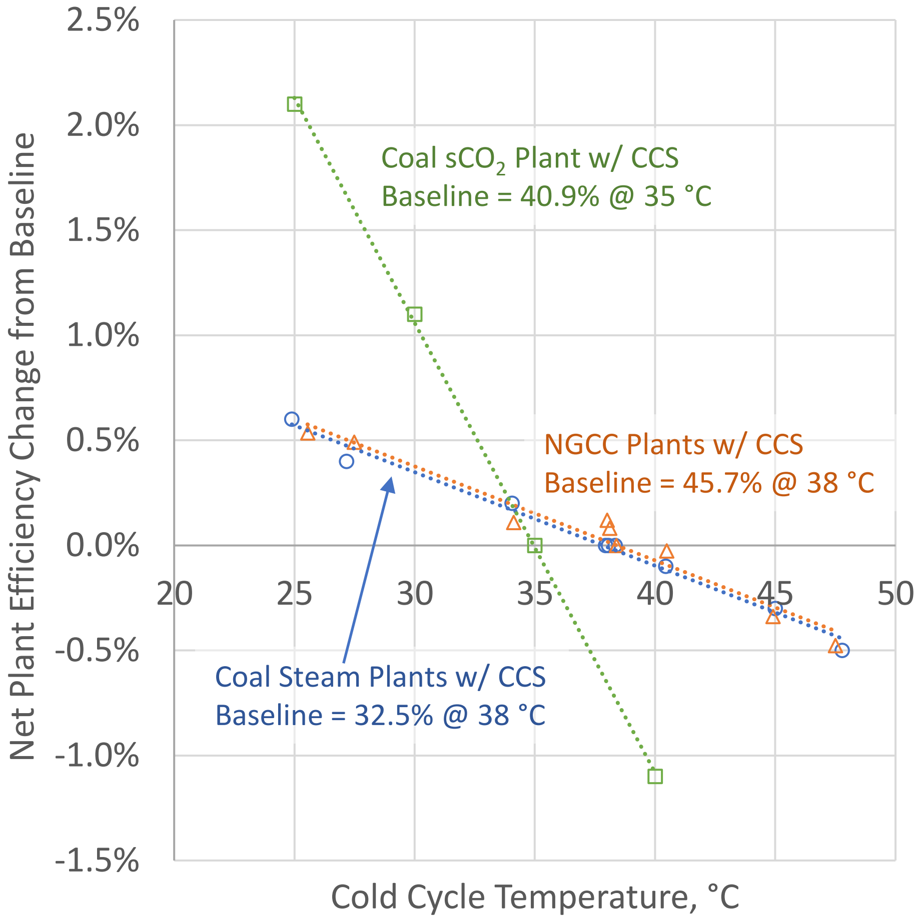
Cooling Systems for sCO_2 Power Cycles

Motivation

- **The efficiency of sCO_2 power cycles is more sensitive to cold cycle temperature than steam- or gas turbine-based power cycles**
  - sCO_2 compression power is very sensitive due to the proximity of operating conditions to the critical point
  - Addition of low-cost cooling capacity can lower the compressor inlet temperature
- **Selection of appropriate cooling system operating conditions require economic optimization**
  - Tradeoff between increase in cooling system capital costs, auxiliary power consumption and decrease in cycle compression power requirements

Source: NETL



Study Objectives

- **Conduct techno-economic analysis for utility-scale natural gas direct-fired sCO_2 power plants**
  - Optimize the cost of electricity (COE) as a function of the sCO_2 cooler outlet temperature (compressor inlet temperature)
  - Optimize cooling system operating conditions for different cooling technologies considered for this study
    - Indirect wet cooling technology
    - Indirect dry cooling technology
    - Direct dry cooling technology
    - Direct wet (Adiabatic) cooling technology

Originally developed for indirect-fired sCO_2 power cycles[1]

Cooler type	Operation	
Direct (air)	Dry	Wet
Indirect (water)	Dry	Wet

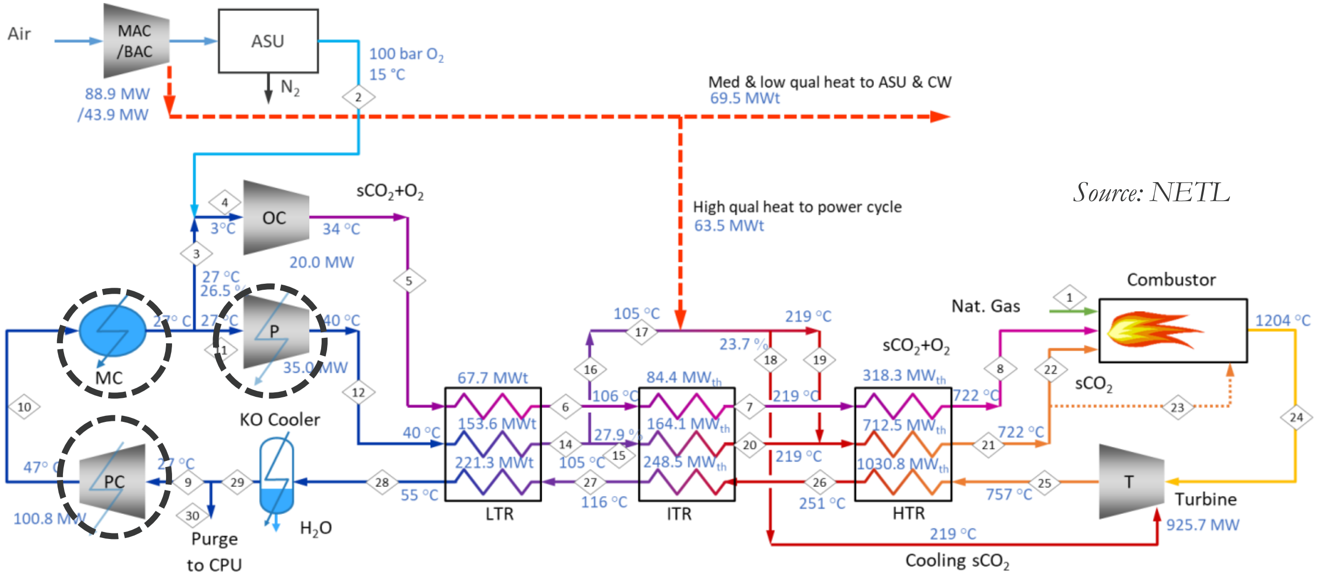
- **Expected Impacts**
  - Shows importance of cooling system optimization for reduction of COE
  - Published cooling system models will enable similar COE optimization by other researchers

[1] S. R. Pidaparti, C. W. White, A. O'Connel, N. T. Weiland and others, "Cooling system cost and performance models for economic sCO2 plant optimization of cooling with respect to cold sCO2 temperature," in *3rd European Conference on Supercritical CO2 (sCO2) Power Systems 2019: 19th-20th September 2019*

Modeling Approach

Design and Assumptions

- **High pressure cryogenic ASU supplies oxygen at 100 bar**
  - Oxygen is pre-mixed with portion of sCO_2 recycle stream (O_2 mole fraction of 23.5%)
- **Cycle recuperators modeled as counterflow PCHEs**
  - 1-D discretized model is used to calculate *UA* and detect internal pinch points
  - Recuperation train split into three stages (LTR, ITR and HTR) to manage the thermal pinch points
- **A steady-state model of the plant was developed using Aspen Plus®**



Source: NETL

Modeling Approach

Design and Assumptions, Cont'd

- **Physical property methods**
  - LK-PLOCK for sCO_2 power cycle
  - PENG-ROB for BOP
- **Ambient conditions: Midwestern U.S[3]**
  - Average dry bulb temperature = 15°C
  - Relative humidity = 60% (Wet bulb temperature = 10.8°C)
  - Ambient pressure = 1.01325 bar
- **Combustor, turbine and rest of the plant modeling details can be found in the paper[2]**

Section	Parameter	Baseline sCO_2 cycle
Combustor	O_2 purity	99.5%
	Excess O_2	1%
	Pressure drop	689 kPa (100 psi)
	Heat loss	Zero
Turbine	Inlet temperature	1204°C (2200°F)
	Inlet pressure	30 MPa (4351 psi)
	Outlet pressure	2.94 MPa (426 psi)
	Blade cooling	Empirical model
Recuperators	Maximum temperature	760°C (1400°F)
	Minimum Temp approach	10°C (18°F)
CO_2 Coolers/Intercoolers	sCO_2 outlet temperature	35°C (95°F), 26.7°C (80°F), 20°C (68°F)
Oxidant compressor (Non-intercooled)	Volumetric oxygen content	23.5%
	Inlet pressure	10 MPa
	Outlet pressure	30.82 MPa
	Isentropic efficiency	85%
Compression train (Includes pre-compressor and pump)	Inlet pressure	2.8 MPa
	Outlet pressure	30.82 MPa
	Isentropic efficiency	85%
	Stages	6 (5 intercooled)
CPU	Impurities	10 ppm O_2 max.

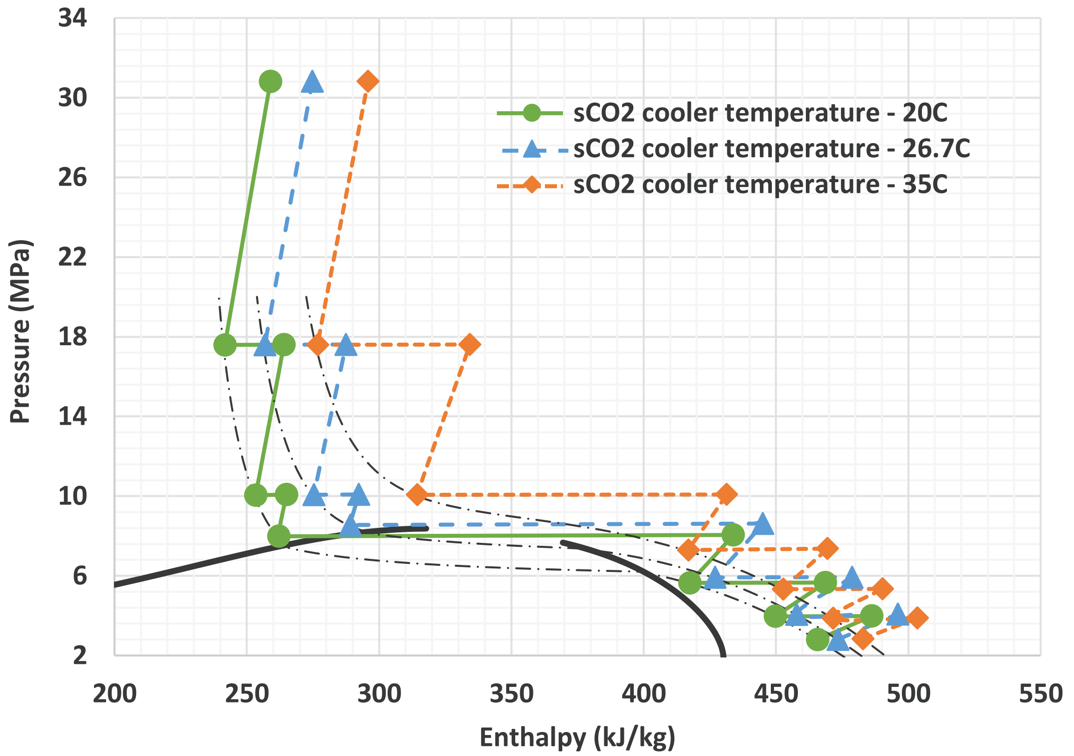
[2] White, Charles, and Nathan Weiland. "Preliminary cost and performance results for a natural gas fired direct sCO2 power plant." In *Proceedings of the 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, USA*, pp. 27-29. 2018.

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

Modeling Approach

Design and Assumptions, Cont'd

- **Compression and cooling train includes following:**
  - Pre-compressor with three stages of intercooling (PCIC1, PCIC2, PCIC3)
  - Main Cooler (MC)
  - Pump with single stage of intercooling (PIC1)
- **Compression train pressure profiles adjustments are made to:**
  - Maximize cycle efficiency for different cooler temperatures
  - Provide split stream for mixing with oxygen from ASU
- **Cooling train operating conditions for different cooler temperatures can be found in the paper**



Modeling Approach

Economic Analysis

- **Based on steady-state modeling results, operating conditions of the cycle and balance of plant (BOP) are used to estimate equipment capital costs**
  - Standard NETL cost estimating methodology[4] is used to calculate the total plant cost (TPC) which includes the capital costs, installation, contractor fees and contingencies
  - COE includes contributions from capital costs, fixed operation and maintenance (O&M) costs, variable O&M costs and fuel costs
    - Capacity factor (CF) = 85%, NG price = $6.13/MMBtu
- **sCO_2 power cycle components capital costs are calculated using algorithms developed under prior work for indirect sCO_2 power cycle applications[5]**
  - Further details of the economic analysis methodology can be found in the paper
- **Cooling system capital costs and auxiliary power are calculated using excel spreadsheet models (available for public use)**

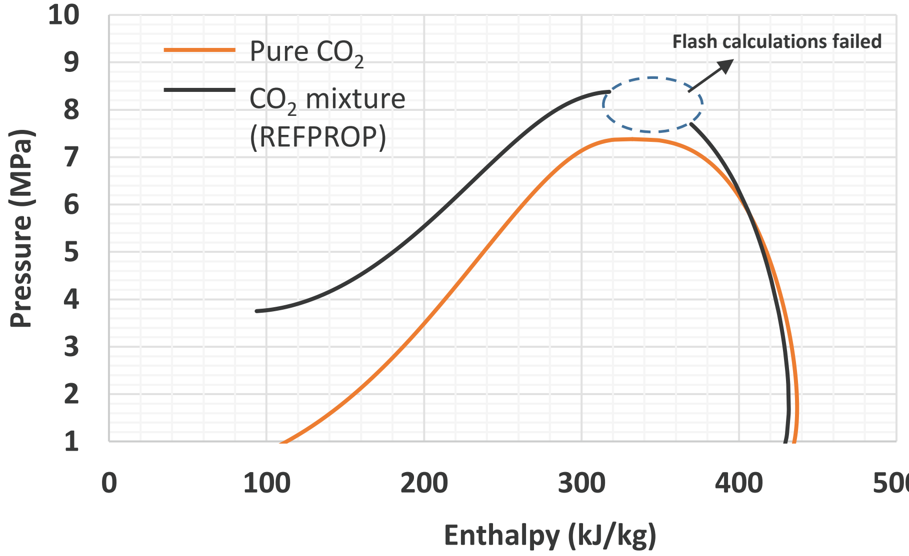
[4] National Energy Technology Laboratory (NETL), *"Quality Guidelines for Energy System Studies, Cost Estimation Methodology for NETL Assessments of Power Plant Performance,"* NETL, Pittsburgh, January 2013

[5] Weiland, Nathan T., Blake W. Lance, and Sandeep R. Pidaparti. "sCO2 Power Cycle Component Cost Correlations From DOE Data Spanning Multiple Scales and Applications." In *ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition*. American Society of Mechanical Engineers Digital Collection, 2019.

Modeling Approach

Cooling System Models

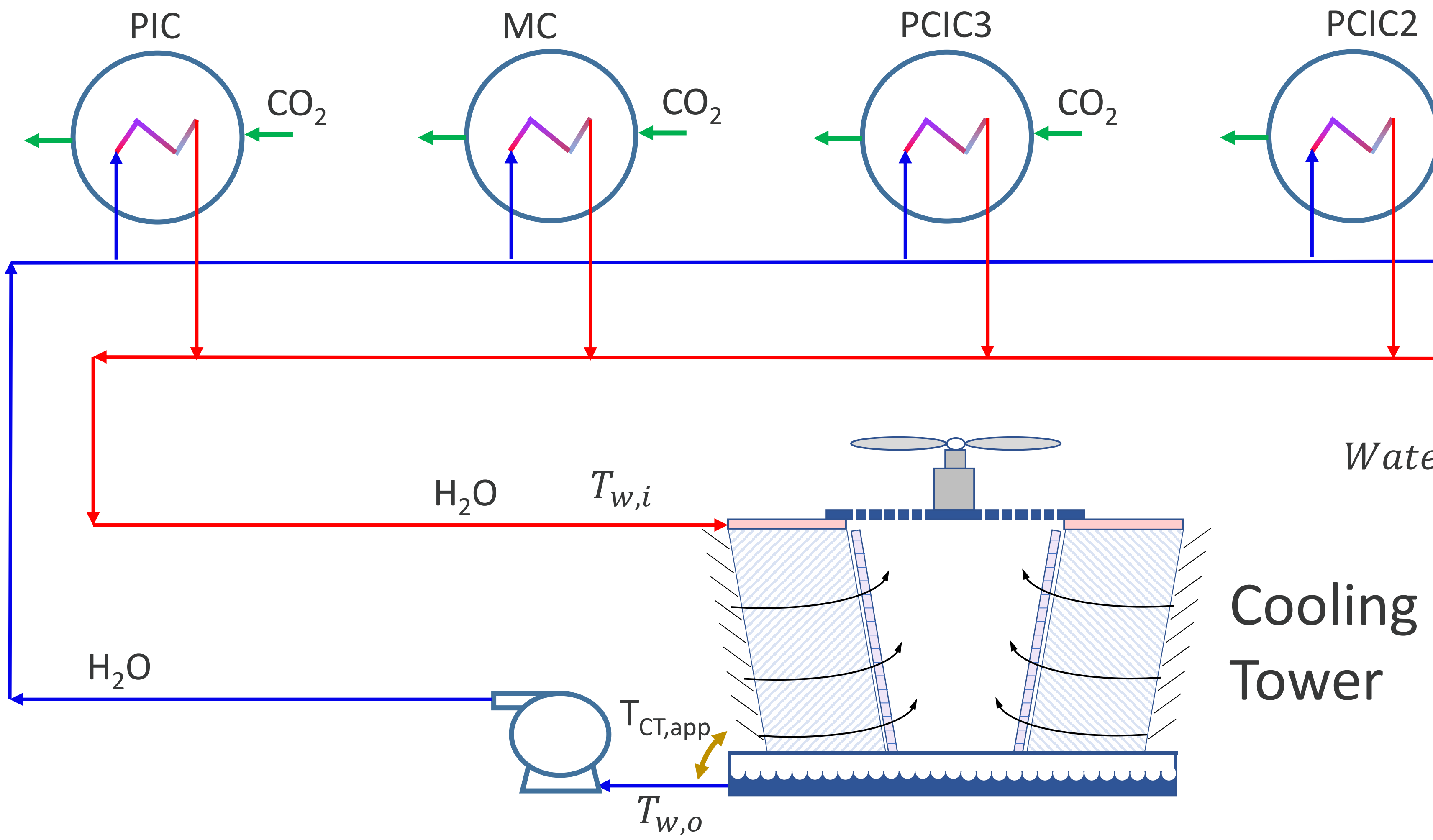
- **Cooling systems models use REFPROP v10 for modeling of sCO_2 mixture properties**
  - Models validated with vendor data and other software packages (for pure sCO_2 working fluid)[1]
  - Calculates cooling system capital cost and auxiliary power consumption
- **Water vapor is excluded from the mixtures for cooling technology models**
  - Flash calculations failed for sCO_2 mixtures near the critical point
  - Expected to have minor impact of TEA since water vapor is only a small fraction of the sCO_2 mixtures (typically <0.2 mol%)



[1] S. R. Pidaparti, C. W. White, A. O'Connel, N. T. Weiland and others, "Cooling system cost and performance models for economic sCO2 plant optimization of cooling with respect to cold sCO2 temperature," in *3rd European Conference on Supercritical CO2 (sCO2) Power Systems 2019: 19th-20th September 2019*

Indirect Wet Cooling Technology

Schematic



$$Water\ flow\ rate = Duty/(Range * Cp)$$

$$Range = T_{w,i} - T_{w,o}$$

$$T_{CT,app} = T_{w,o} - T_{wb}$$

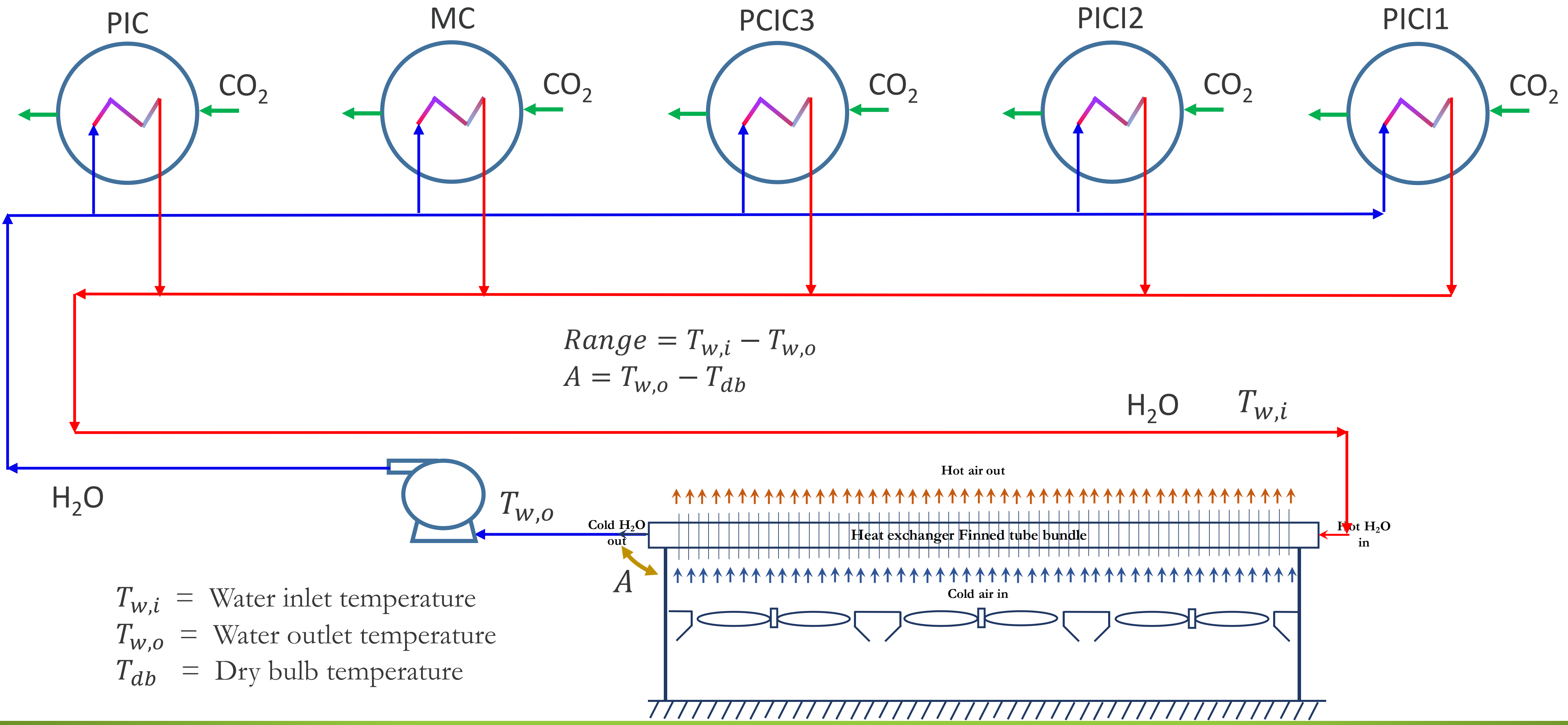
$T_{w,i}$ = Water inlet temperature

$T_{w,o}$ = Water outlet temperature

T_{wb} = Wet bulb temperature

Indirect Dry Cooling Technology

Schematic



$$Range = T_{w,i} - T_{w,o}$$
$$A = T_{w,o} - T_{db}$$

$T_{w,i}$ = Water inlet temperature

$T_{w,o}$ = Water outlet temperature

T_{db} = Dry bulb temperature

Indirect Wet and Dry Cooling Technologies

Coolers Modeling

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- **For indirect cooling technologies, water is assumed as the intermediate heat transfer fluid and a water/sCO_2 PCHE cooler is required**
  - Water/sCO_2 cooler UA calculated from a discretized 1-D counterflow PCHE model, with also check for internal temperature crosses
  - Cooler cost scaled with $UA = Q/LMTD$
- **Balance of plant (BOP) cooling load is handled by a separate cooling tower**
  - True for all four cooling technologies
  - Includes sCO_2 power cycle water knockout cooler, CPU cooling load, ASU intercoolers and chiller condenser
  - BOP cooling tower Range – 11.1°C (20°F)
  - BOP cooling tower Approach – 4.7°C (8.5°F)

Indirect Wet and Dry Cooling Technologies

Optimization Variables

- **Water range (water flow rate) for five individual sCO_2 coolers**
  - Impacts the size and cost of coolers, cooling tower/ACHE

$$Water\ flow\ rate = Duty/(Range * Cp)$$

- **Cooling tower water approach (to wet bulb temperature) and ACHE water approach (to dry bulb temperature)**
  - Impacts the size and cost of coolers, cooling tower/ACHE
  - Cooling tower approach lower limit set to 2.8°C (5°F)
  - Cooling tower range upper limit set to 27.8°C (50°F)

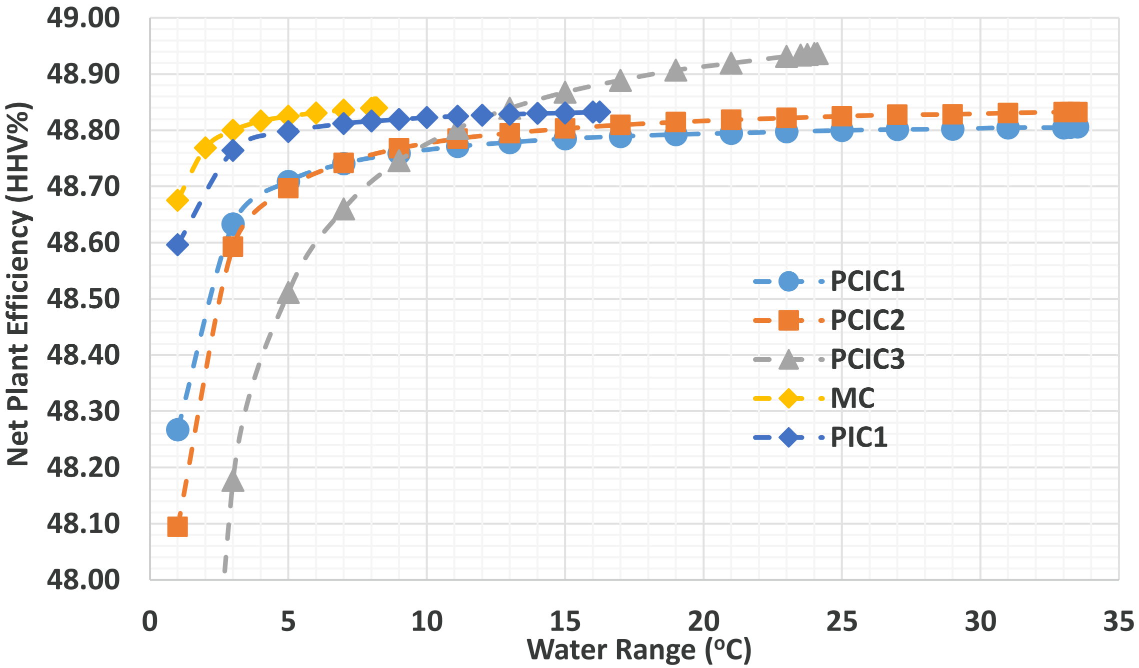
Optimization Variable	Impacts
PCIC1 Range	PCIC1, cooling tower/ACHE size and cost
PCIC2 Range	PCIC2, cooling tower/ACHE size and cost
PCIC3 Range	PCIC3, cooling tower/ACHE size and cost
MC Range	MC, cooling tower/ACHE size and cost
PIC1 Range	PIC1, cooling tower/ACHE size and cost
Cooling Tower/ACHE Approach	sCO_2 coolers, cooling tower/ACHE size and cost

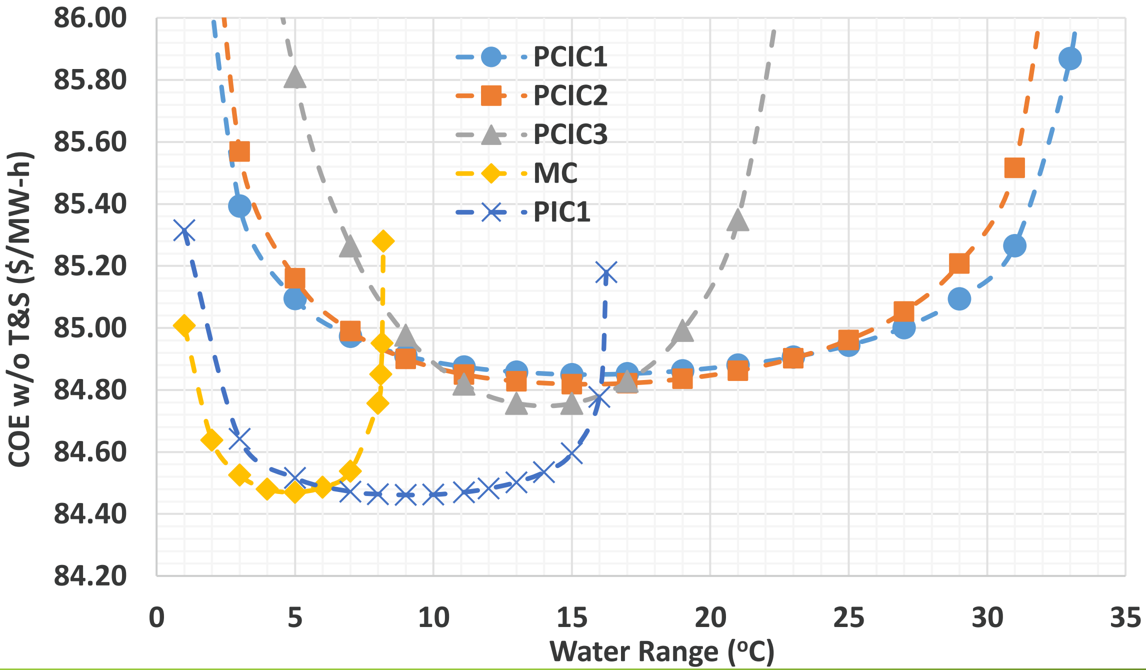
Cooling tower/ACHE range is not an optimization variable explicitly — it is calculated based on the energy balance

Indirect Wet Cooling Technology

Sample Results

- **Effect of water range on plant efficiency and COE (Cooler temperature = 20°C, CT approach = 4.7°C)**
  - Net plant efficiency decreases exponentially as the water range decreases (increased water flow, cooling fan and water pump power)
  - COE goes through a local minimum with respect to each cooler water range (Opposing trends between cooler and cooling tower capital costs)

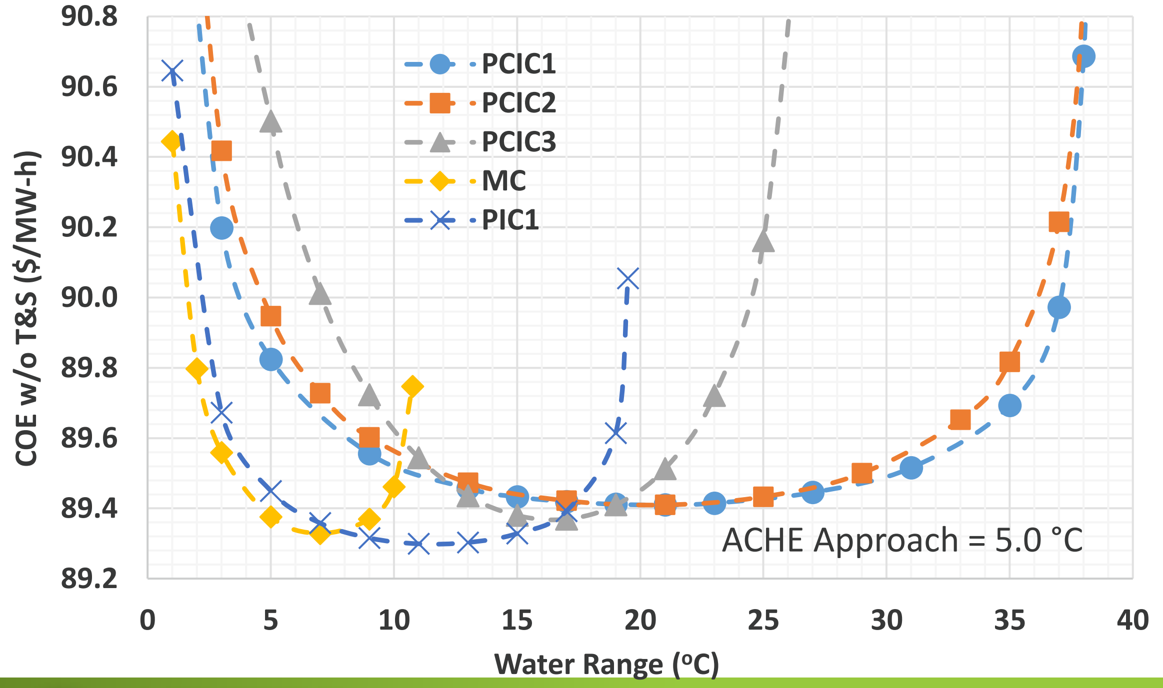


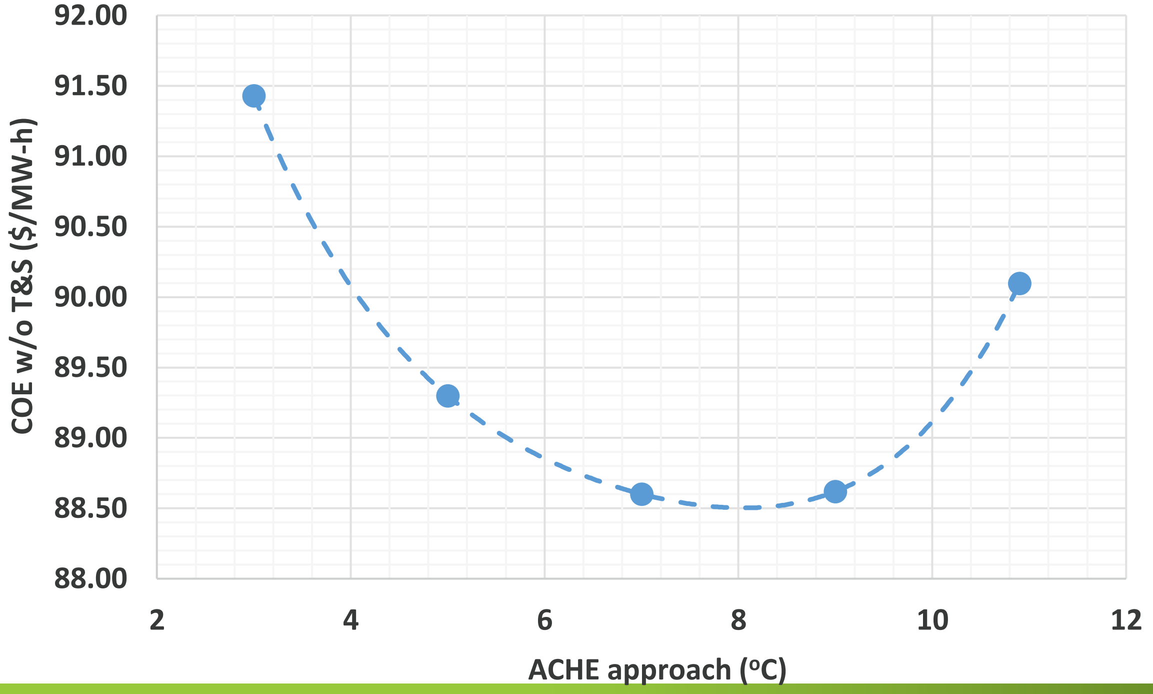


Indirect Dry Cooling Technology

Sample Results

- **Effect of water range, ACHE approach on COE (Cooler temperature = 26.7°C)**
  - COE goes through a minimum with respect to each cooler water range and ACHE approach temperature
    - Due to opposing cost trends between cooler and ACHE capital costs
- **Optimization repeated for different sCO_2 cooler temperatures**





Indirect Wet and Dry Cooling Technologies

Summary

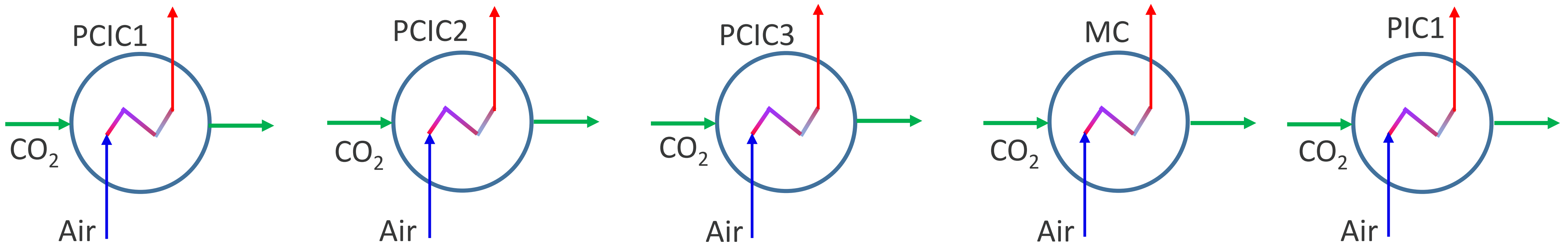
- **Optimized wet cooling technology parameters are listed in the table below**
  - Optimum range, ACHE approach values increase with cooler temperature
  - Optimum cooling tower approach is set to the lower limit of 2.8°C (5°F) for all cooler temperatures

sCO_2 Cooler Temperature	Optimized Cooling Technology Parameters (Indirect wet cooling)						
	CT Approach (°C)	PCIC1 Range (°C)	PCIC2 Range (°C)	PCIC3 Range (°C)	MC Range (°C)	PIC1 Range (°C)	CT Range (°C)
20.0°C	2.8 (5°F)	19.0 (34.2°F)	17.0 (30.6°F)	17.0 (30.6°F)	6.0 (10.8°F)	11.0 (19.8°F)	15.6 (28.0°F)
26.7°C	2.8 (5°F)	23.0 (41.4°F)	25.0 (45.0°F)	21.0 (37.8°F)	11.0 (19.8°F)	15.0 (27.0°F)	19.9 (35.8°F)
35.0°C	2.8 (5°F)	25.0 (45.0°F)	25.0 (45.0°F)	25.0 (45.0°F)	25.0 (45.0°F)	25.0 (45.0°F)	25.0 (45.0°F)

sCO_2 Cooler Temperature	Optimized Cooling Technology Parameters (Indirect dry cooling)						
	ACHE Approach (°C)	PCIC1 Range (°C)	PCIC2 Range (°C)	PCIC3 Range (°C)	MC Range (°C)	PIC1 Range (°C)	ACHE Range (°C)
20.0°C	4.0 (7.2°F)	13.0 (23.4°F)	13.0 (23.4°F)	11.0 (19.8°F)	3.0 (5.4°F)	7.0 (12.6°F)	10.1 (18.1°F)
26.7°C	7.0 (12.6°F)	17.0 (30.6°F)	17.0 (30.6°F)	13.0 (23.4°F)	5.0 (9.0°F)	9.0 (16.2°F)	12.2 (21.9°F)
35.0°C	13.0 (23.4°F)	17.0 (30.6°F)	17.0 (30.6°F)	17.0 (30.6°F)	15.0 (27.0°F)	13.0 (23.4°F)	15.4 (27.8°F)

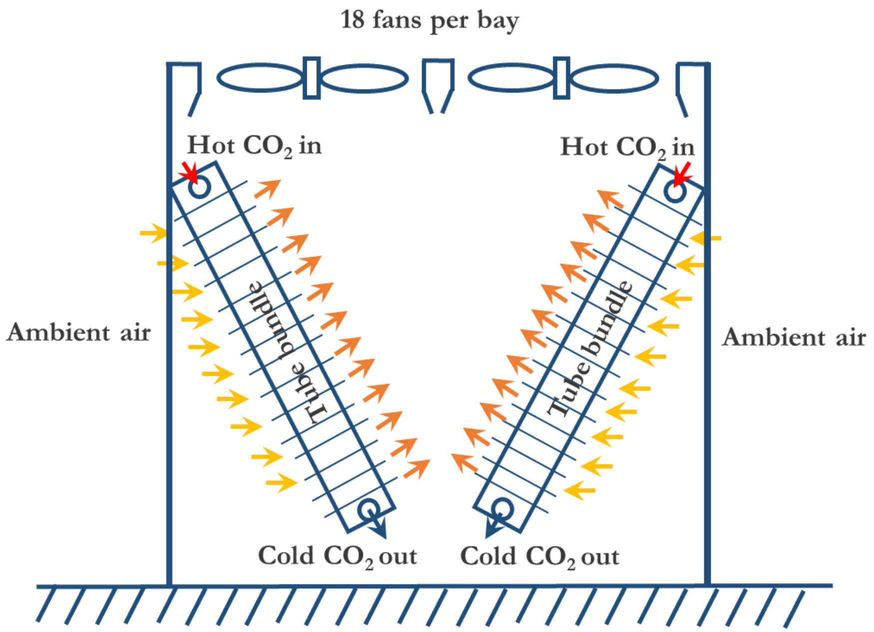
Direct Dry Cooling Technology

Schematic



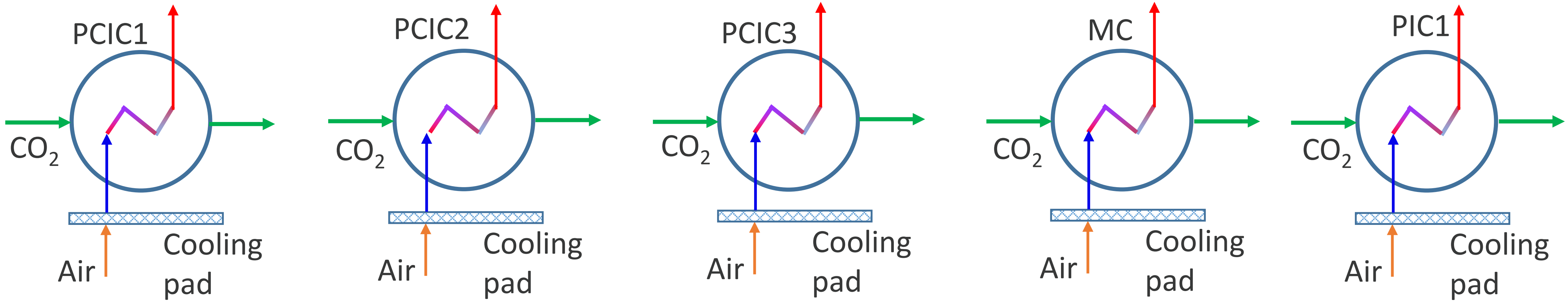
- **Optimization variables for direct dry cooling technology**
  - Volumetric flow rate of air for five individual sCO_2 coolers

Optimization Variable	Impacts
PCIC1 air flow rate	PCIC1 size and cost
PCIC2 air flow rate	PCIC2 size and cost
PCIC3 air flow rate	PCIC3 size and cost
MC air flow rate	MC size and cost
PIC1 air flow rate	PIC1 size and cost



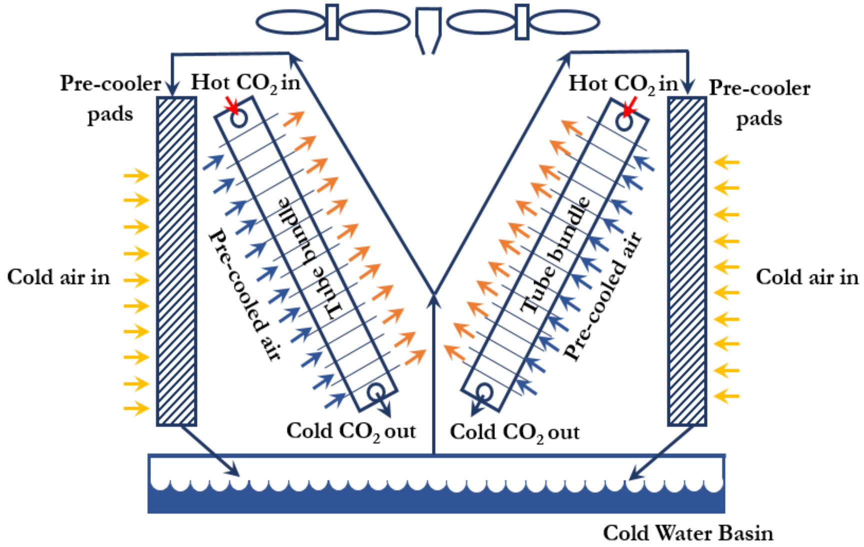
Direct Wet (Adiabatic) Cooling Technology

Schematic



- **Optimization variables for adiabatic cooling technology**
  - Volumetric flow rate of air for five individual sCO_2 coolers

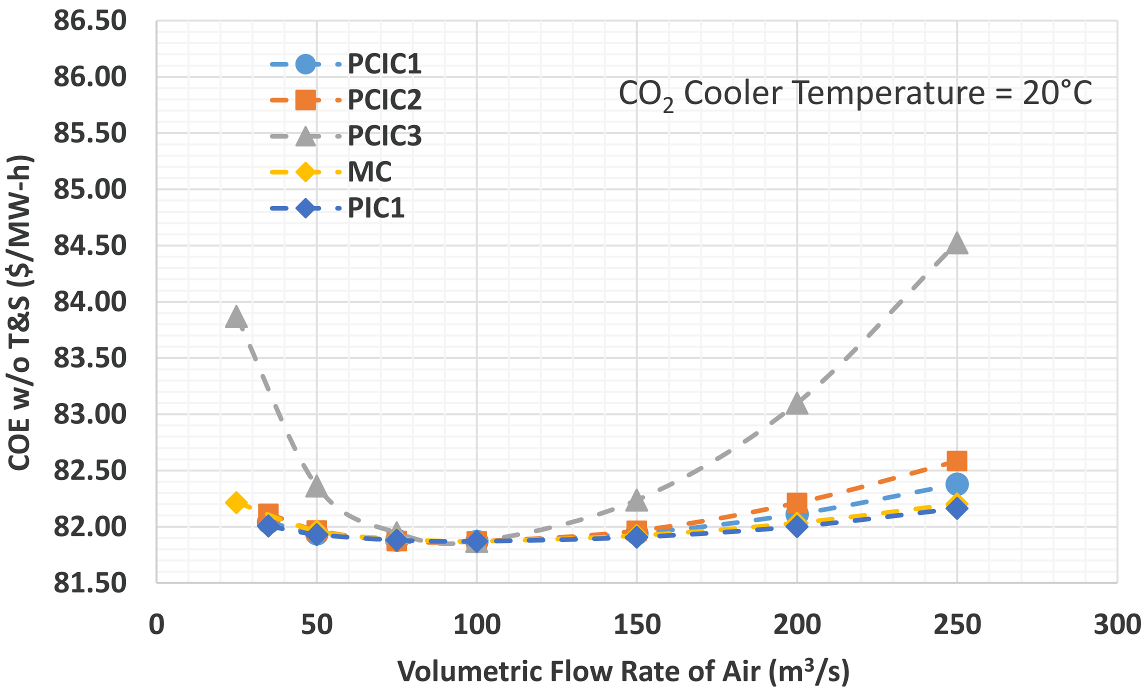
Optimization Variable	Impacts
PCIC1 air flow rate	PCIC1 size and cost
PCIC2 air flow rate	PCIC2 size and cost
PCIC3 air flow rate	PCIC3 size and cost
MC air flow rate	MC size and cost
PIC1 air flow rate	PIC1 size and cost



Direct Dry and Adiabatic Cooling

Summary

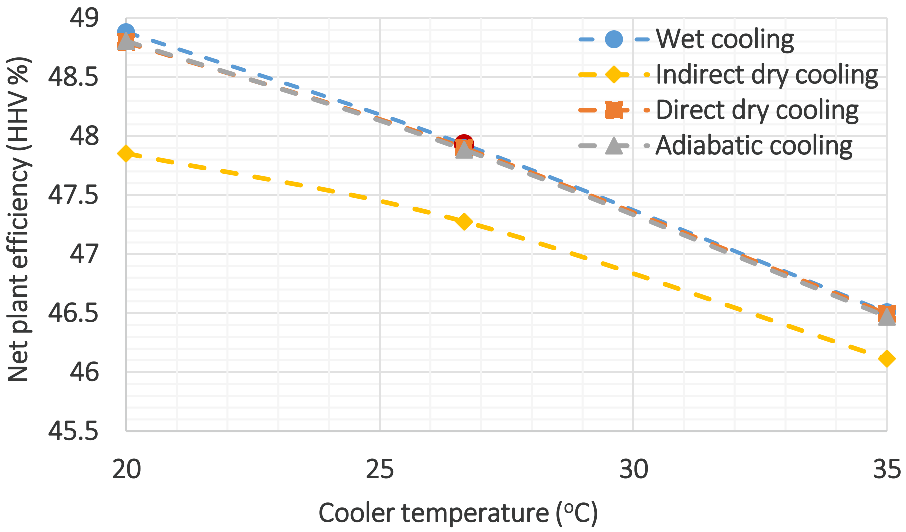
- **COE goes through a minimum at optimum air flow rate per each bay**
  - Due to opposite trends of cooler costs and plant efficiency
  - Optimum air flow rate per bay is in the range of 90-100 m^3/s (function of tube bundle and fan characteristics)

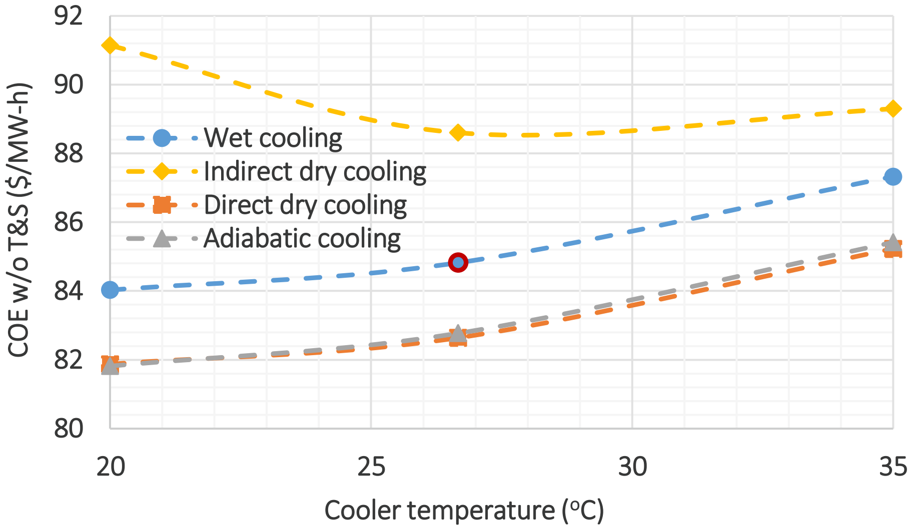


Cooling Technology Comparison

Efficiency and COE Optimization Results

- **Plots show optimized plant efficiency and COE at each cooler temperature**
  - Valid only for the selected ambient conditions
- **For all four cooling technologies, plant efficiency increases as the sCO_2 cooler temperature decreases**
- **For indirect wet cooling, direct dry, and adiabatic cooling technology, the COE decreased as the sCO_2 cooler temperature decreases**
  - Indirect dry cooling technology exhibited a minimum COE for cooler temperature of 26.7°C

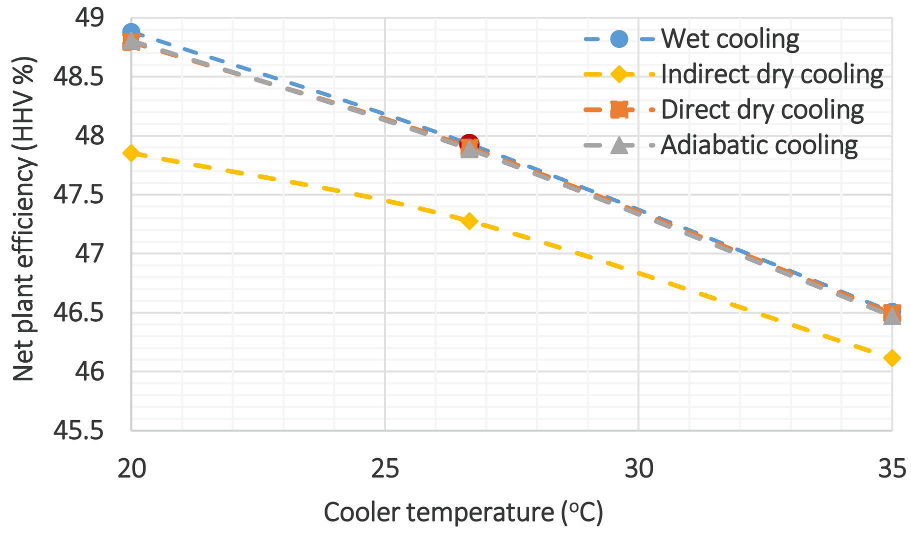


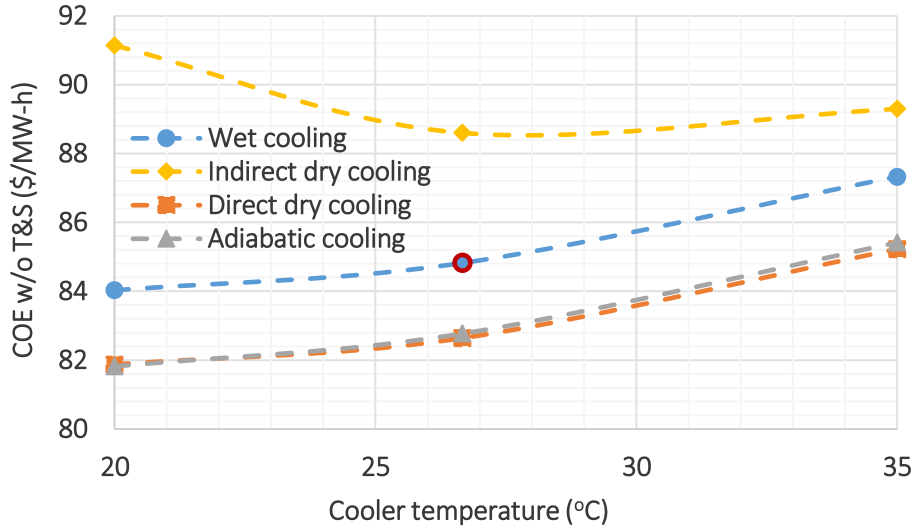


Cooling Technology Comparison

Efficiency and COE Optimization Results, Cont'd

- **Out of the four cooling technologies, direct cooling technologies (dry and wet) offered lowest COE**
- **Depending on cooling technology, lowering the cooler temperature from 35°C to 20°C:**
    - Improves the plant efficiency by ~2.5 percentage points
    - COE is reduced by as much as 4.2%
    - Demonstrates benefit of condensing CO_2 cycle operation provided ambient conditions allow for it





Summary and Future Work

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- **Summary**
  - Developed four cooler spreadsheet models for minimizing sCO_2 power plant COE by optimizing CO_2 cooler temperature and cooling system operating conditions
  - Cooler models available for public use along with the technical documentation (Links provided in the paper)
  - Improvements in plant efficiency (up to 2.5 percentage points) and plant COE (up to 4.2%) highlight the importance of cooling system design and optimization
- **Future Work**
  - Incorporation of cooling system optimization with other component improvements to further optimize the COE of natural gas direct sCO_2 plants
  - Investigation of cooling system optimization for different plant sites and ambient conditions
  - Use of cooling system models to predict off-design performance

Acknowledgements

- The authors would like to thank Travis Shultz[1], Richard Dennis[1], Eric Liese[1], and Mark Woods[1,2] for their support and assistance in performing this work.

[1]National Energy Technology Laboratory

[2]NETL Support Contractor

QUESTIONS/ COMMENTS

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