



# Performance and Cost Potential of sCO<sub>2</sub> Bottoming Cycle for Gas Turbines with Carbon Capture – Paper 32



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# Agenda

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- Objective and Scope
- Screening Analysis Summary
- Levelized cost of electricity (LCOE) Optimization using FOQUS
- Performance and Economic Comparison
  - Optimized Cases versus Reference Plant (B32B.95 Case from Rev4a Baseline Study)
- Impact of Gas Turbine Exhaust Gas Temperature
- Conclusions and Further Recommendations

# Objective and Scope

- **Objective**

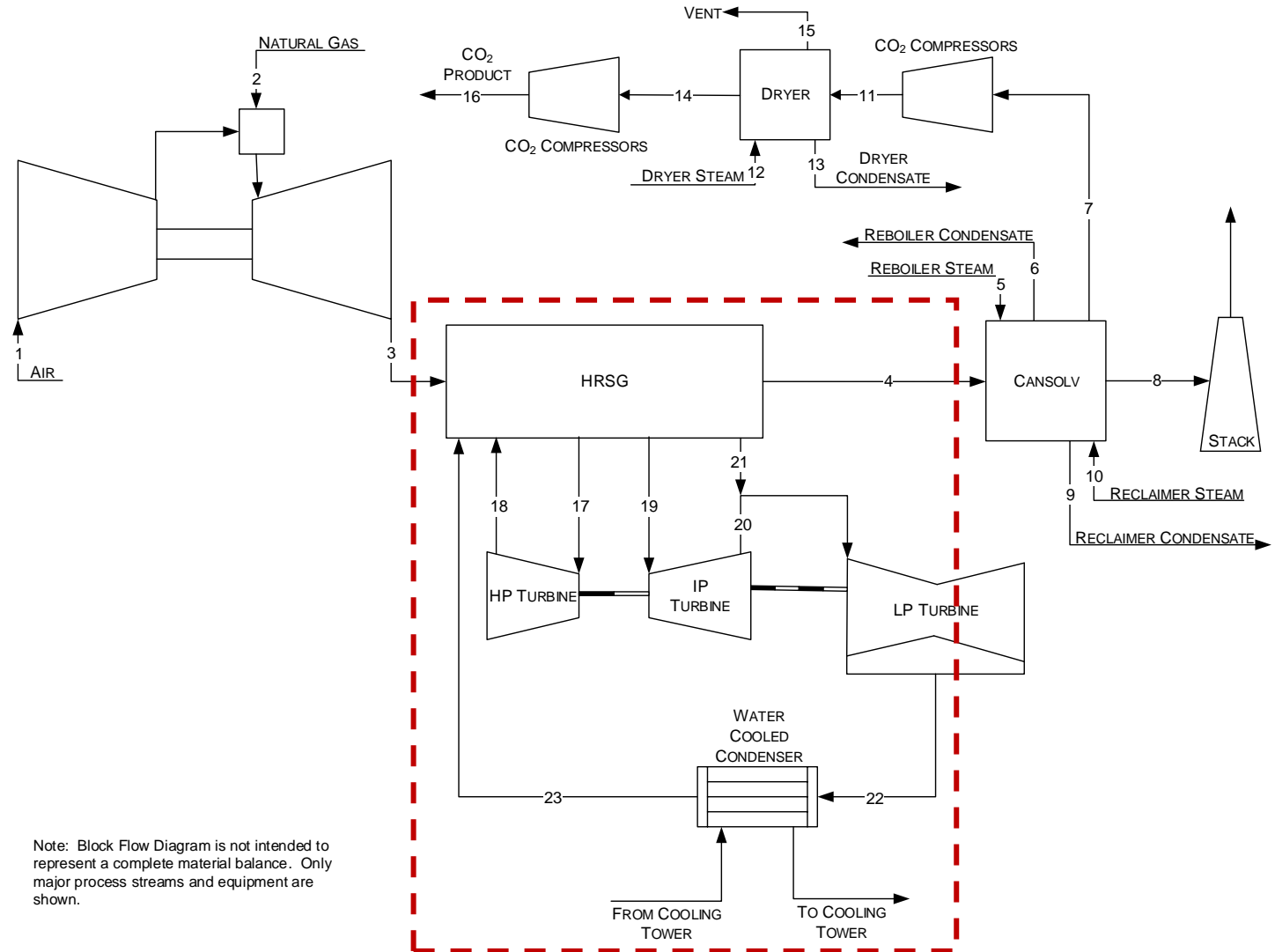
- Evaluate the performance and cost potential of the indirect  $s\text{CO}_2$  power cycle as a bottoming cycle for advanced utility scale gas turbines (H-Class) with CCS
- Minimize LCOE

- **Scope**

- Leveraged previous work which investigated  $s\text{CO}_2$  bottoming cycle for F-class gas turbine without capture
- A combined  $s\text{CO}_2$  cycle for power and steam generation for capture system reboiler duty

# Reference Case

- Case B32B from NETL Rev4A Baseline Study with 95% CO<sub>2</sub> capture†. 2-on-1 NGCC
- H-Class gas turbine
- Exhaust gas temperature = 596°C
- Triple-pressure steam re-heat cycle power generation
  - Steam turbine inlet temperature = 585°C
- Necessary LP steam for Cansolv system extracted from steam cycle
- Ambient temperature 15°C is assumed



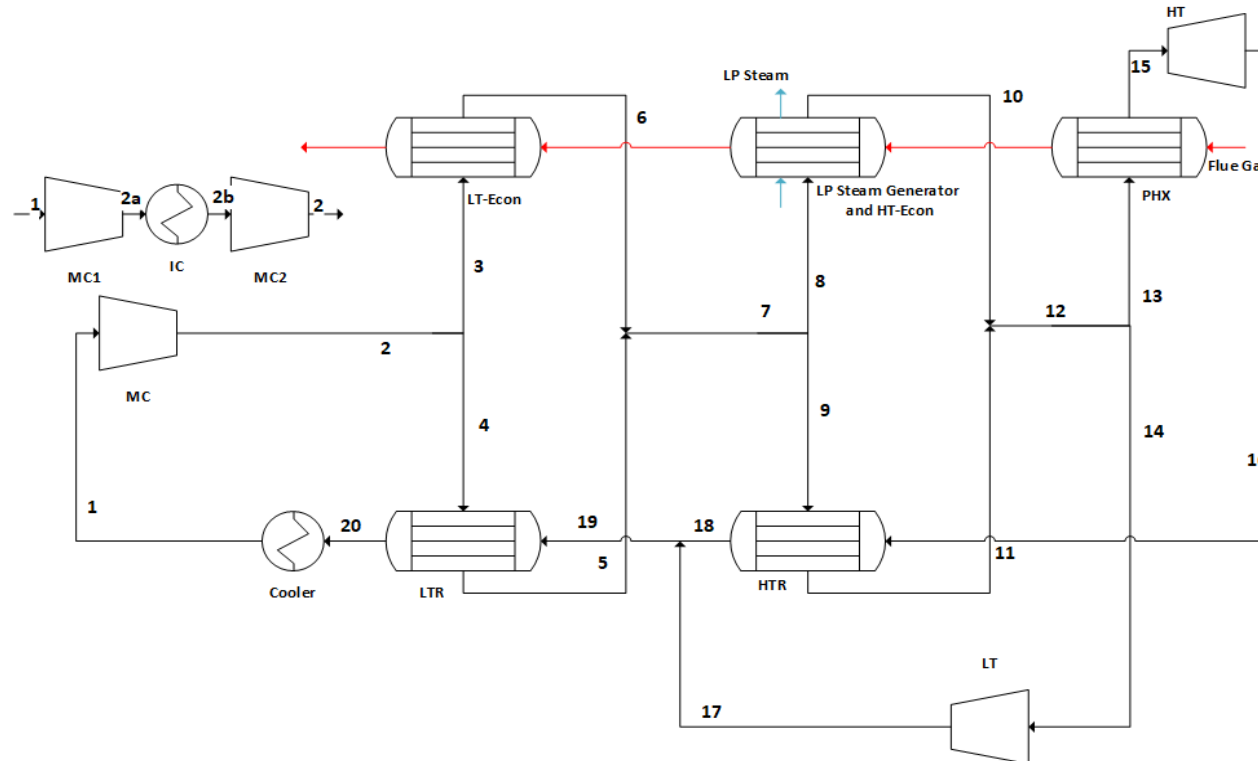
Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

The image features a series of high-voltage power transmission towers, also known as pylons, silhouetted against a dramatic sunset sky. The towers are arranged in a perspective that recedes into the distance, creating a sense of depth. The sky transitions from a deep orange near the horizon to a dark blue at the top, with scattered clouds catching the low light. The overall mood is industrial and serene.

# Screening Analysis Summary

# Cycle configuration(s)

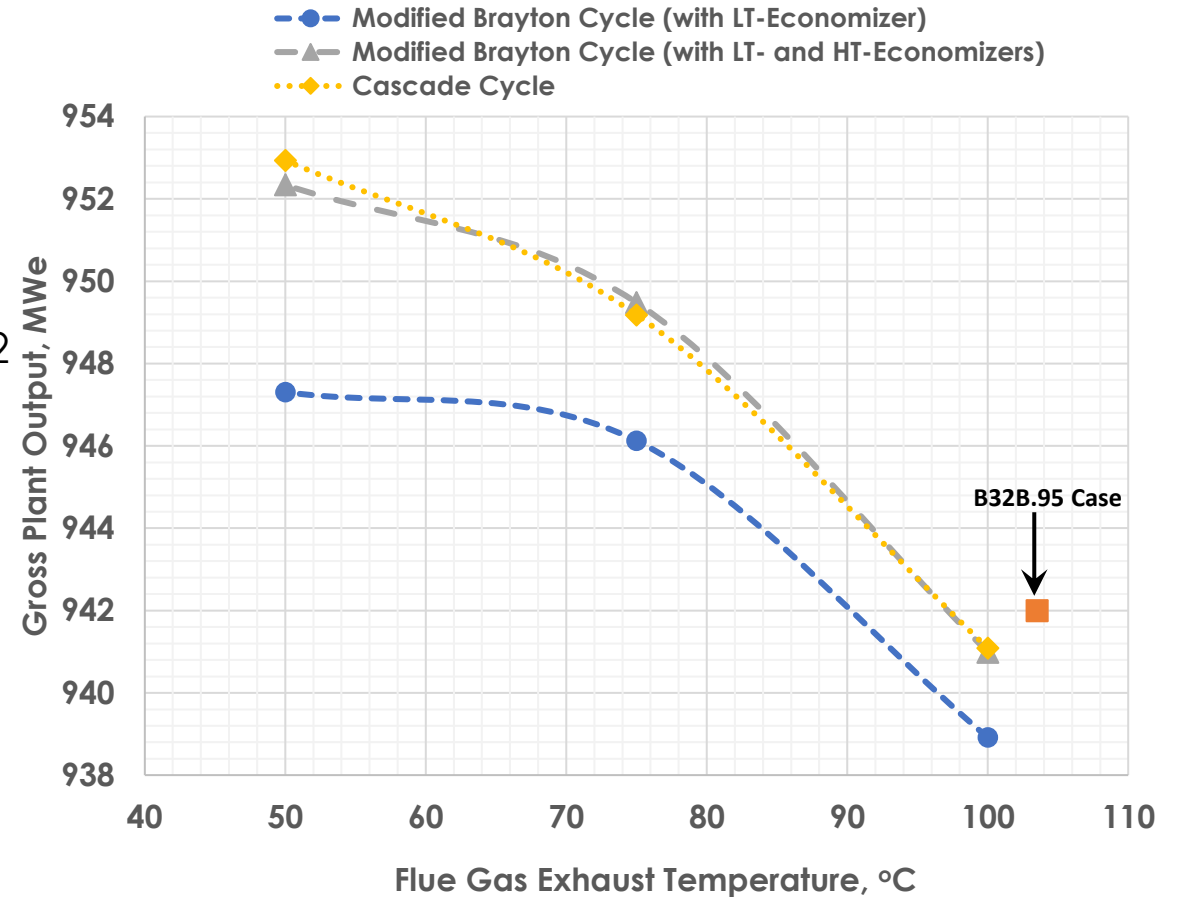
- Three sCO<sub>2</sub> power cycle configurations are considered for screening analysis
  - Cascade cycle shown in figure
  - “Modified Brayton” cycle with LT- and HT-Economizers (no LT-Turbine)
  - “Modified Brayton” cycle with LT-Economizer (no LT-Turbine or HT-Economizer)





# Screening Analysis – Summary

- Spreadsheet models were used to maximize power output for each of the configuration as a function of flue gas exhaust temperature
- sCO<sub>2</sub> cycles lead to more effective heat recovery from flue gas and sCO<sub>2</sub> turbine exhaust than reference plant (B32B.95 Case)

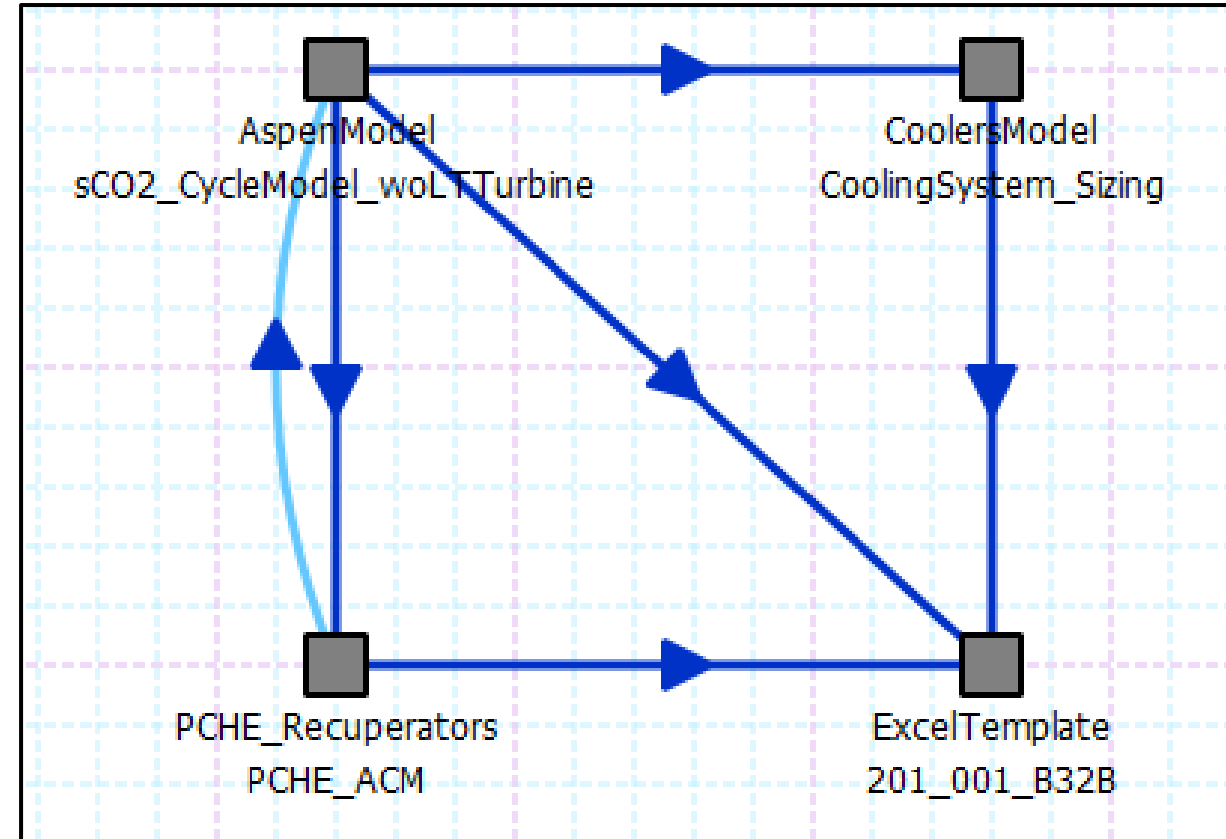


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# LCOE Optimization Using FOQUS

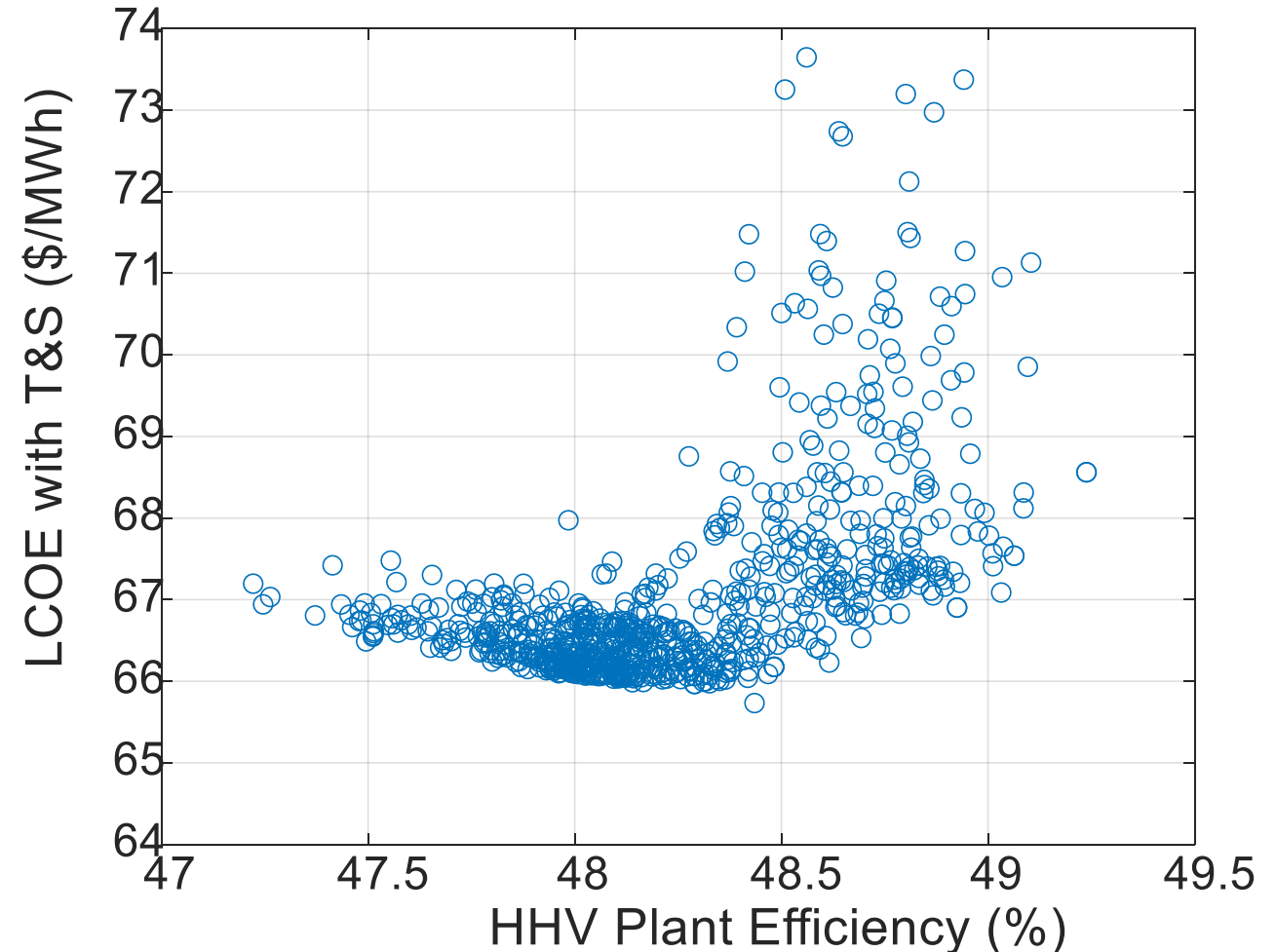
# NETL Software FOQUS Used for Optimization

- Final FOQUS model includes four nodes
  - Plant Aspen Plus® model
    - Single model for all the sCO<sub>2</sub> cycle configurations
  - PCHE Aspen Custom models
    - Calculates HTR, LTR size, mass
  - Adiabatic Cooler system Excel model
    - Calculates cooling system aux power, water consumption rate and total cost
    - Midwest ISO ambient conditions
  - Performance/cost template
    - Calculates the plant efficiency and LCOE



# Sample Optimization Results

- Objective function:
  - Minimize LCOE
  - No constraints applied
  - Optimization algorithm used: CMA-ES (Evolutionary algorithm)
- Sample results plotted for Modified Brayton (LT-Econ) case
  - Close to 1,000 samples computed for this case
  - HHV plant efficiencies >49.0% possible with higher LCOE



# Optimized Design Variables

Design Variables	Flue gas exhaust temperature = 50.0 °C			
	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle	
Turbine inlet temperature	$TIT, \text{ }^\circ\text{C}$	537.0	563.5	587.1
Cooler outlet temperature	$T_{cooler}, \text{ }^\circ\text{C}$	18.8	20.6	21.6
Cycle max pressure	$P_{max}, \text{ MPa}$	30.1	30.6	27.7
HTR approach temperature	$T_{App,HTR}, \text{ }^\circ\text{C}$	60.0	15.0	13.0
PHX approach temperature	$T_{App,PHX}, \text{ }^\circ\text{C}$	7.3	9.0	15.0
LTR approach temperature	$T_{App,LTR}, \text{ }^\circ\text{C}$	6.4	6.8	7.5
LT-Econ approach temperature	$T_{App,LT-Econ}, \text{ }^\circ\text{C}$	2.8	6.2	4.0
HT-Econ heat duty	$Q_{HT-Econ}, \text{ MW}$	N/A	129.1	215.6
PHX heat duty	$Q_{PHX}, \text{ MW}$	470.1	362.9	276.4
HTR total pressure drop	$\Delta P_{HTR}, \text{ bar}$	3.2	2.9	1.9
LTR total pressure drop	$\Delta P_{LTR}, \text{ bar}$	1.2	1.2	2.2
Main cooler pressure drop	$\Delta P_{MC}, \text{ bar}$	0.049	0.045	0.049
Compressor intercooler pressure drop	$\Delta P_{MCIC}, \text{ bar}$	0.5	1.2	1.1
Flow split fraction to LT turbine	$X_{LT}$	N/A	N/A	20.6%

The image features a series of high-voltage power transmission towers, also known as pylons, silhouetted against a dramatic sky at sunset or sunrise. The towers are arranged in a perspective that recedes into the distance, creating a sense of depth. The sky transitions from a deep blue at the top to a bright orange and yellow near the horizon, with scattered clouds catching the low light. The overall mood is industrial yet serene.

# Performance and Economic Comparison (Optimized Cases)

# Performance Summary

- sCO<sub>2</sub> power cycles have slightly lower plant efficiency
  - Feedwater/condensate pumps are not needed for the sCO<sub>2</sub> power cycles
  - Inclusion of valves for off-design operation reduced cycle efficiency slightly
- Modified Brayton cycle with only LT-Economizer offered highest plant efficiency

Performance Summary	B32B95 Case	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle
Combustion Turbine Power, MWe	686.0	686.0	686.0	686.0
sCO <sub>2</sub> /Steam Power Cycle, MWe	256.0	245.0	242.0	241.0
<b>Total Gross Power, MWe</b>	<b>942.0</b>	<b>931.0</b>	<b>927.0</b>	<b>926.0</b>
Circulating Water Pumps, kWe	5,570	3,620	3,620	3,620
Combustion Turbine Auxiliaries, kWe	1,320	1,320	1,320	1,320
Condensate Pumps, kWe	200	–	–	–
Cooling Tower Fans, kWe	2,880	1,870	1,870	1,870
Adiabatic Cooling System, kWe	–	2,496	2,501	1,950
CO <sub>2</sub> Capture/Removal Auxiliaries, kWe	19,200	19,200	19,200	19,200
CO <sub>2</sub> Compression, kWe	25,130	25,130	25,130	25,130
Feedwater Pumps, kWe	5,760	–	–	–
Ground Water Pumps, kWe	520	430	430	420
Miscellaneous Balance of Plant, kWe	710	710	710	710
SCR, kWe	3	3	3	3
sCO <sub>2</sub> /Steam Turbine Auxiliaries	230	230	230	230
Transformer Losses, kWe	3,020	2,970	2,960	2,950
<b>Total Auxiliaries, MWe</b>	<b>65</b>	<b>58</b>	<b>58</b>	<b>57</b>
<b>Net Power, MWe</b>	<b>877</b>	<b>873</b>	<b>869</b>	<b>868</b>
<b>Net Plant (HHV) Efficiency (%)</b>	<b>48.7%</b>	<b>48.4%</b>	<b>48.2%</b>	<b>48.2%</b>
Combustion Turbine (HHV) Efficiency, %	38.0%	38.0%	38.0%	38.0%
Raw water consumption, gpm/MW <sub>net</sub>	4.3	3.9	3.8	3.8
Natural Gas Feed Flow, kg/hr (lb/hr)	124,605	124,605	124,605	124,605

# Economic Summary

- sCO<sub>2</sub> power cycle capital cost is higher than that of steam Rankine cycle
  - HRSG cost lower due to lower overall UA
  - Feedwater and cooling water system costs are lower
- Modified Brayton with only LT-Economizer has lowest CAPEX on \$/kWe basis

Cost Account Description	B32B95 Case	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle
<b>Capital Costs (TPC, \$/1000)</b>				
Feedwater & Miscellaneous BOP	\$139,816	\$117,385	\$117,229	\$116,921
Flue Gas Cleanup & Piping	\$588,429	\$571,598	\$571,598	\$571,598
Combustion Turbine & Accessories	\$220,813	\$220,813	\$220,813	\$220,813
HRSG, Ductwork, & Stack	\$168,537	\$129,104	\$159,527	\$163,872
Steam/sCO <sub>2</sub> Turbine & Accessories	\$87,607	\$160,351	\$152,039	\$167,315
Cooling Water System	\$59,145	\$45,436	\$45,413	\$45,407
Accessory Electric Plant	\$86,659	\$82,146	\$82,122	\$81,718
Instrumentation & Control	\$25,072	\$24,672	\$24,671	\$24,635
Improvement & Site	\$33,192	\$33,009	\$32,951	\$32,927
Buildings & Structure	\$20,691	\$20,157	\$20,051	\$19,998
<b>Total</b>	<b>\$1,429,961</b>	<b>\$1,404,649</b>	<b>\$1,426,415</b>	<b>\$1,445,204</b>
<b>Total, \$/kWe</b>	<b>\$1,630</b>	<b>\$1,610</b>	<b>\$1,641</b>	<b>\$1,665</b>



# sCO<sub>2</sub> Power Cycle Cost Breakdown

- sCO<sub>2</sub> power cycle capital costs are dominated by coolers and recuperators
  - LCOE optimization significantly reduced the CAPEX of these components which might have also reduced the cycle efficiency

Cost Account Description	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle
<b>Capital Costs (TPC, \$/1000)</b>			
Main CO <sub>2</sub> Compressor	\$11,716	\$11,699	\$11,817
High Temperature Recuperator	\$16,047	\$19,206	\$29,929
Low Temperature Recuperator	\$26,719	\$21,061	\$20,261
Adiabatic Coolers	\$77,212	\$70,885	\$73,296
CO <sub>2</sub> Turbine	\$11,926	\$11,989	\$14,834
Piping System	\$12,703	\$12,703	\$12,703
System Foundations	\$4,543	\$4,496	\$4,475
<b>Total</b>	<b>\$160,351</b>	<b>\$152,039</b>	<b>\$167,315</b>
<b>Total, \$/kWe</b>	<b>\$184</b>	<b>\$175</b>	<b>\$193</b>

# LCOE Breakdown

- LCOE of modified Brayton cycle (LT-Econ) is 0.5% lower than reference case (B32B.95)
  - Due to lower plant capital costs
- Other two configurations have 0.6 – 1.4% higher LCOE than the B32B.95 case due to slightly lower efficiencies and higher capital costs

	B32B95 Case	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle
<b>LCOE (\$/MWh)</b>				
Capital	20.6	20.3	20.7	21.0
Fixed O&M	7.0	6.9	7.0	7.1
Variable O&M	3.9	3.8	3.8	3.9
Fuel	31.0	31.1	31.3	31.3
<b>Total (Excluding T&amp;S)</b>	<b>62.4</b>	<b>62.1</b>	<b>62.8</b>	<b>63.3</b>
CO <sub>2</sub> T&S	3.6	3.6	3.6	3.6
<b>Total (Including T&amp;S)</b>	<b>66.0</b>	<b>65.7</b>	<b>66.4</b>	<b>66.9</b>

The image features a series of high-voltage power transmission towers, also known as pylons, silhouetted against a dramatic sky at sunset or sunrise. The towers are arranged in a perspective that recedes into the distance. The sky is filled with soft, colorful clouds in shades of orange, yellow, and blue. The overall mood is industrial and atmospheric.

# Impact of Gas Turbine Exhaust Temperature

# Impact of EGT – Performance

- Higher exhaust gas temperature (EGT) leads to higher bottoming cycle efficiency
  - The plant efficiency increases by ~1.0 percentage point by increasing EGT from 596.0°C to 629.0°C
- Gas turbine data for EGT = 629.0°C case is taken from GT-PRO for GE 7HA.02

Performance Summary	B32B95 Case EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 629.0°C
Combustion Turbine Power, MWe	686.0	686.0	692.0
sCO <sub>2</sub> /Steam Power Cycle, MWe	256.0	245.0	256.0
<b>Total Gross Power, MWe</b>	<b>942.0</b>	<b>931.0</b>	<b>948.0</b>
Circulating Water Pumps, kWe	5,570	3,620	3,620
Combustion Turbine Auxiliaries, kWe	1,320	1,320	1,320
Condensate Pumps, kWe	200	–	–
Cooling Tower Fans, kWe	2,880	1,870	1,870
Adiabatic Cooling System, kWe	–	2,496	3,393
CO <sub>2</sub> Capture/Removal Auxiliaries, kWe	19,200	19,200	19,200
CO <sub>2</sub> Compression, kWe	25,130	25,130	25,130
Feedwater Pumps, kWe	5,760	–	–
Ground Water Pumps, kWe	520	430	480
Miscellaneous Balance of Plant, kWe	710	710	710
SCR, kWe	3	3	3
sCO <sub>2</sub> /Steam Turbine Auxiliaries	230	230	230
Transformer Losses, kWe	3,020	2,970	3,020
<b>Total Auxiliaries, MWe</b>	<b>65</b>	<b>58</b>	<b>59</b>
<b>Net Power, MWe</b>	<b>877</b>	<b>873</b>	<b>889</b>
Net Plant (HHV) Efficiency (%)	48.7%	48.4%	49.4%
Combustion Turbine (HHV) Efficiency, %	38.0%	38.0%	38.4%
Natural Gas Feed Flow, kg/hr (lb/hr)	124,605	124,605	126,432

# Impact of EGT – LCOE Breakdown

- LCOE is also lower for higher EGT
  - Impact of higher EGT on steam bottoming cycle is unknown at this point

	B32B95 Case EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 596.0°C	Modified Brayton (LT-Econ) EGT = 629°C
<b>LCOE (\$/MWh)</b>			
Capital	20.6	20.3	20.0
Fixed O&M	7.0	6.9	6.8
Variable O&M	3.9	3.8	3.8
Fuel	31.0	31.1	31.2
<b>Total (Excluding T&amp;S)</b>	<b>62.4</b>	<b>62.1</b>	<b>61.7</b>
CO <sub>2</sub> T&S	3.6	3.6	3.5
<b>Total (Including T&amp;S)</b>	<b>66.0</b>	<b>65.7</b>	<b>65.2</b>

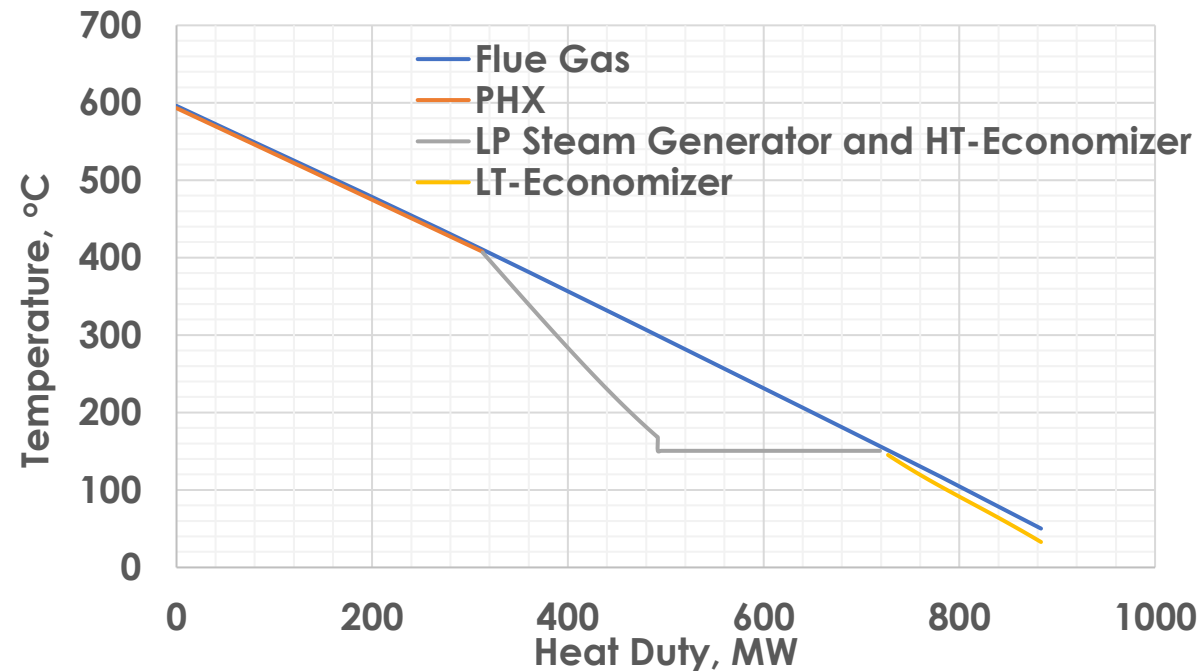
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# Conclusions and Further Recommendations

- For NGCC plants with carbon capture, simpler cycle configurations have lower CAPEX and higher efficiency (while considering CAPEX vs efficiency tradeoffs)
  - Cascade cycles with multiple economizers and turbines might be better suited for plants without CCS (due to need for higher heat recovery)
- Simpler configuration also has a lower  $s\text{CO}_2$  turbine inlet temperature
  - Could reduce startup time and material fatigue
- Higher gas turbine exhaust temperature is needed for  $s\text{CO}_2$  power cycles to be more attractive both in terms of performance and cost
  - H-class gas turbine selected in this study has an exhaust temperature of  $596^\circ\text{C}$  which limits the  $s\text{CO}_2$  cycle turbine inlet temperature
  - A duct fired burner could be considered

# Further Recommendations

- Generating LP steam for solvent recovery leads to inefficient heat recovery
  - Could high pressure  $s\text{CO}_2$  be used as heat source for solvent regeneration?
  - Plan to conduct a thermodynamic evaluation of the concept





# Acknowledgments

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This work was performed in support of the U.S. Department of Energy's (DOE) Fossil Energy and Carbon Management's Turbines program and executed through the National Energy Technology Laboratory (NETL) Research & Innovation Center's Supercritical CO<sub>2</sub> Field Work Proposal.

# QUESTIONS/ COMMENTS

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# Extra Slides

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# Economic Assumptions

- Capital costs for the sCO<sub>2</sub> power cycle components are based on correlations published in 2019 ASME Turbo Expo paper
  - Primary heater costs are based on correlation developed using GT-Pro and vendor data (See next slide)
- Capital cost scaling of the balance-of-plant equipment was conducted using reference capital costs from reference case (B32B.95)
  - Scaling parameters are taken from latest NETL QGESS documents
- Plants are assumed to have a capacity factor of 85%
- Natural gas fuel cost = \$4.42/MMBtu
- Captured CO<sub>2</sub> transportation and storage (T&S) cost is assumed to be \$10/tonne CO<sub>2</sub> (from Midwest to Illinois Basin)
- The Aspen model and Excel templates will be subjected to QA/QC