Performance and Cost Potential of sCO_2 Bottoming Cycle for Gas Turbines with Carbon Capture – Paper 32

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Agenda

- Objective and Scope
- Screening Analysis Summary
- 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 sCO_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 sCO_2 bottoming cycle for F-class gas turbine without capture
  - A combined sCO_2 cycle for power and steam generation for capture system reboiler duty

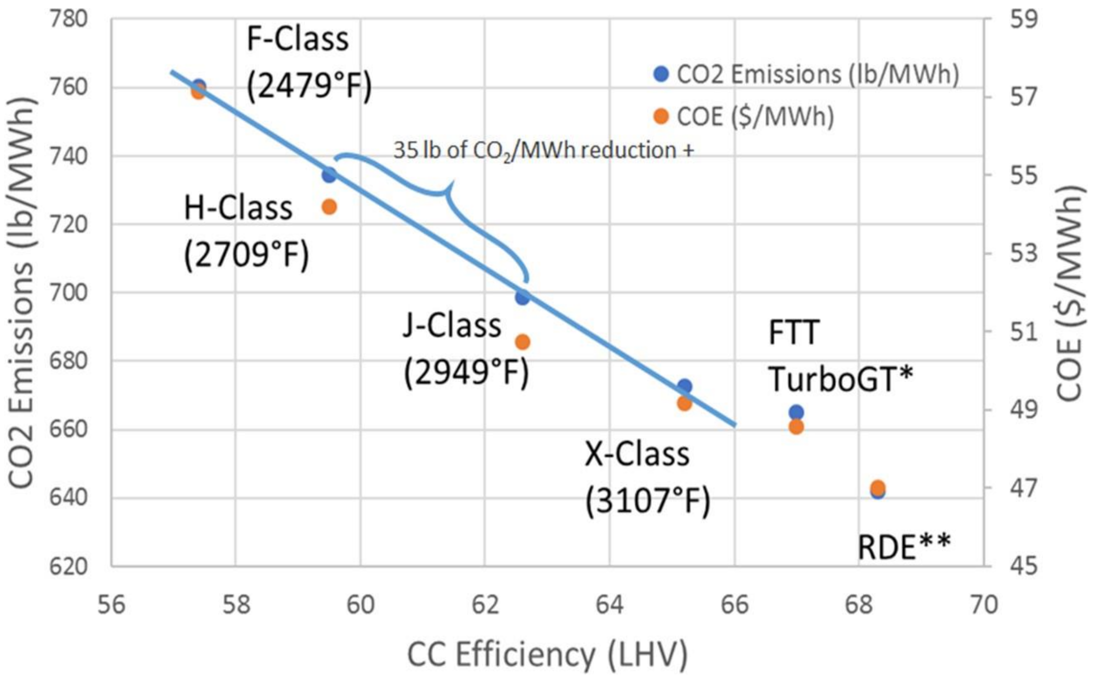
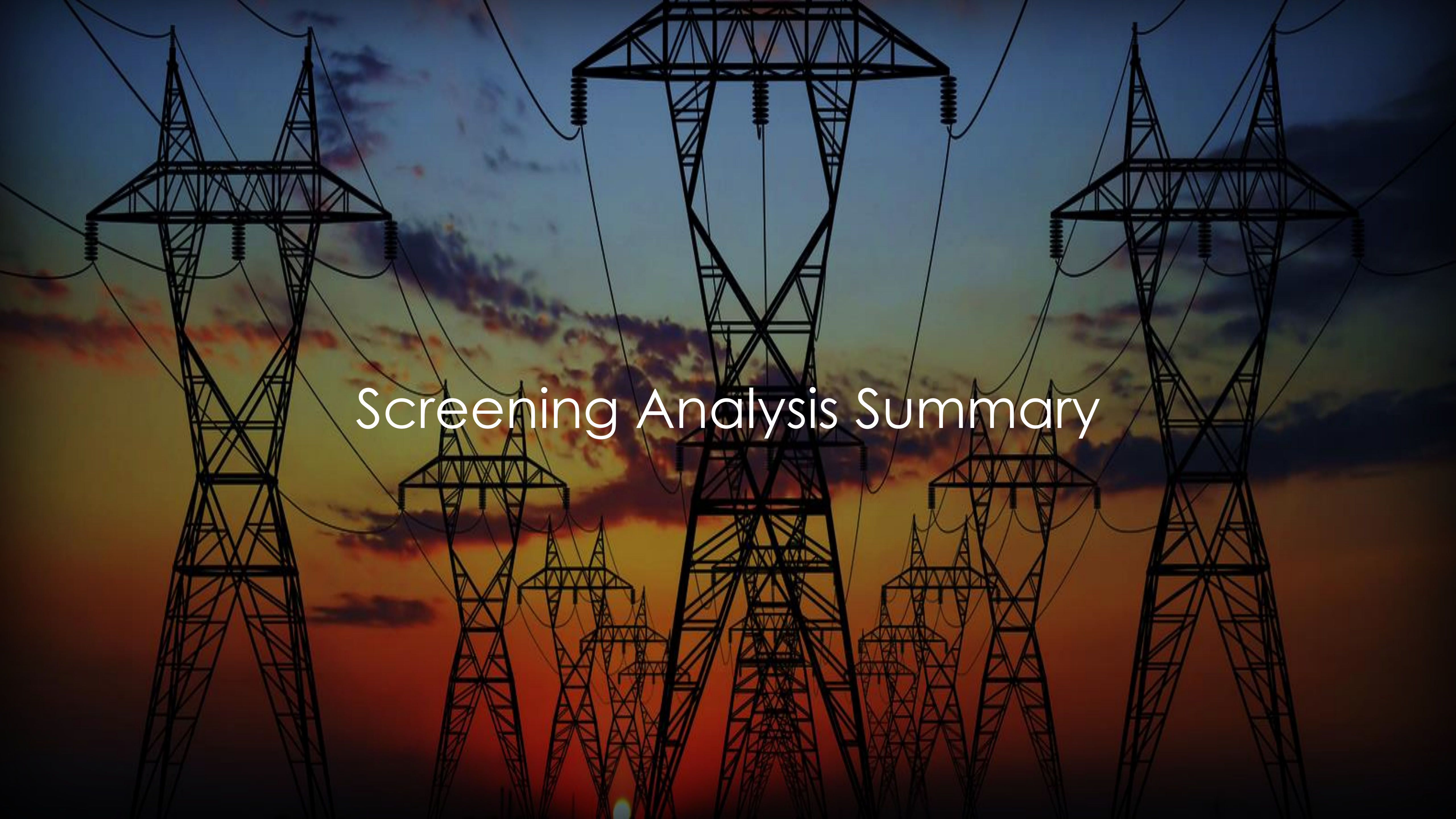


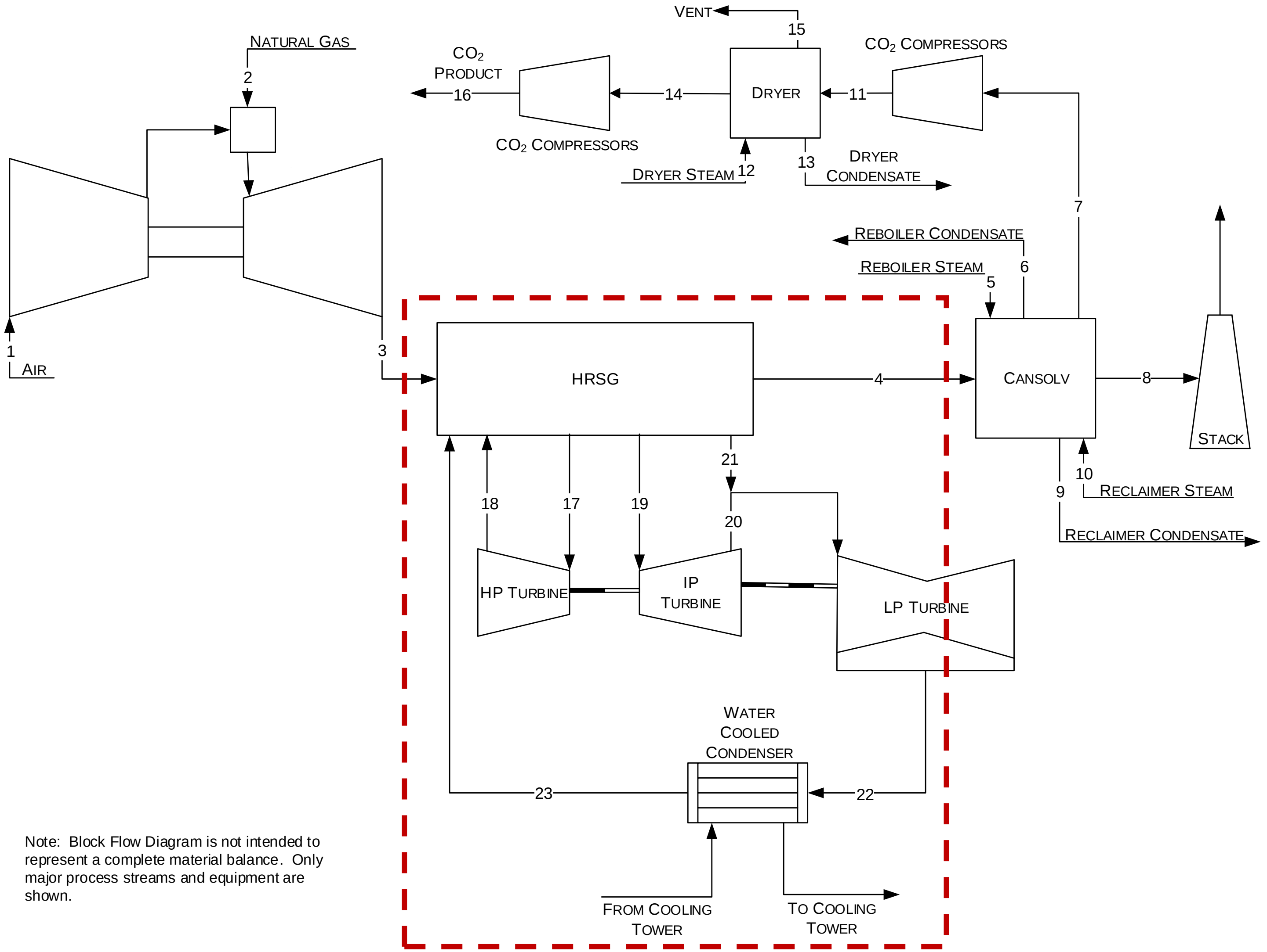
Figure is for natural gas fueled machines and illustrative of the impact of efficiency and firing temperature on efficiency and COE

Screening Analysis Summary



Reference Case

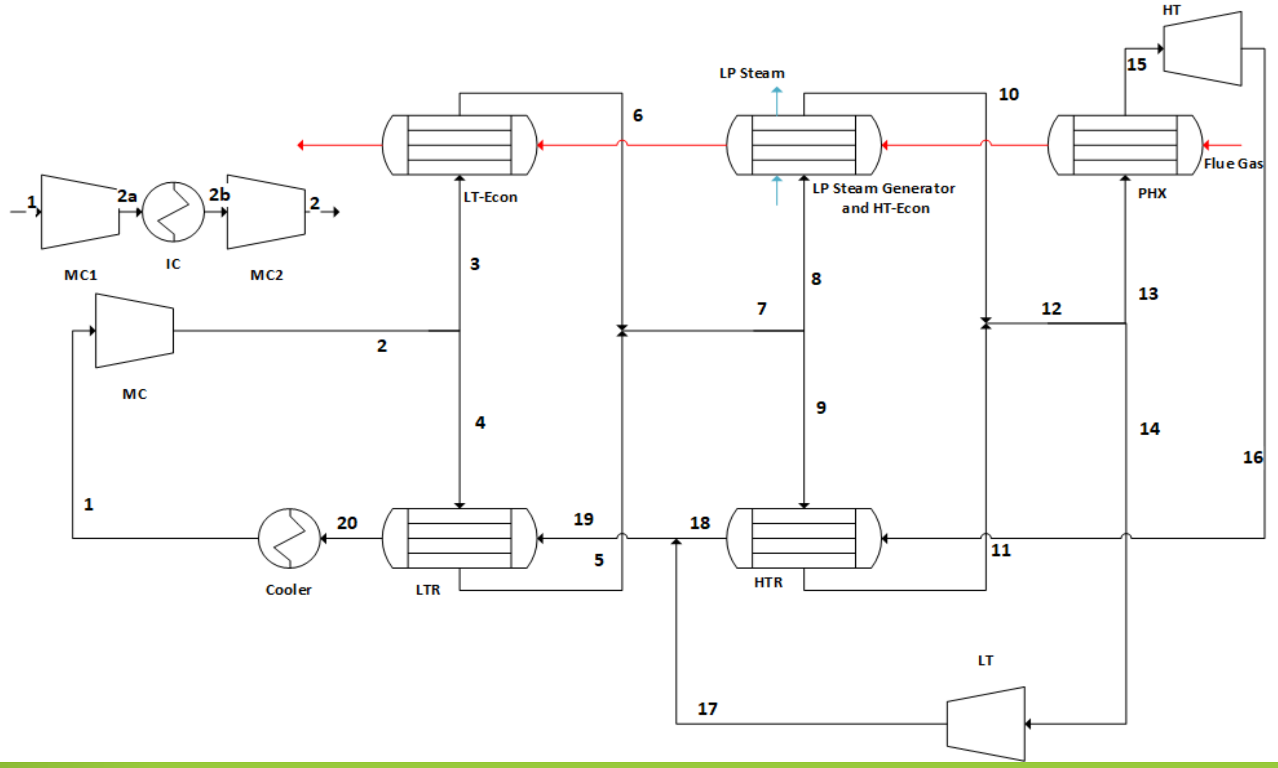
- Case B32B from NETL Rev4A Baseline Study with 95% CO_2 capture†. 2-on-1 NGCC
- H-Class gas turbine
- Exhaust gas temperature = 596°C (added 629°C case)
- Triple-pressure steam re-heat cycle power generation
  - Steam turbine inlet temperature = 585°C
- Necessary LP steam for Cansolv system extracted from steam cycle
- Ambient temperature 15°C is asumed



†Baseline Studies Overview | netl.doe.gov (https://netl.doe.gov/node/7512)

Cycle configuration(s)

- Three sCO_2 power cycle configurations are considered for screening analysis
  - Cascade cycle shown in figure (Echogen Concept)
  - “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

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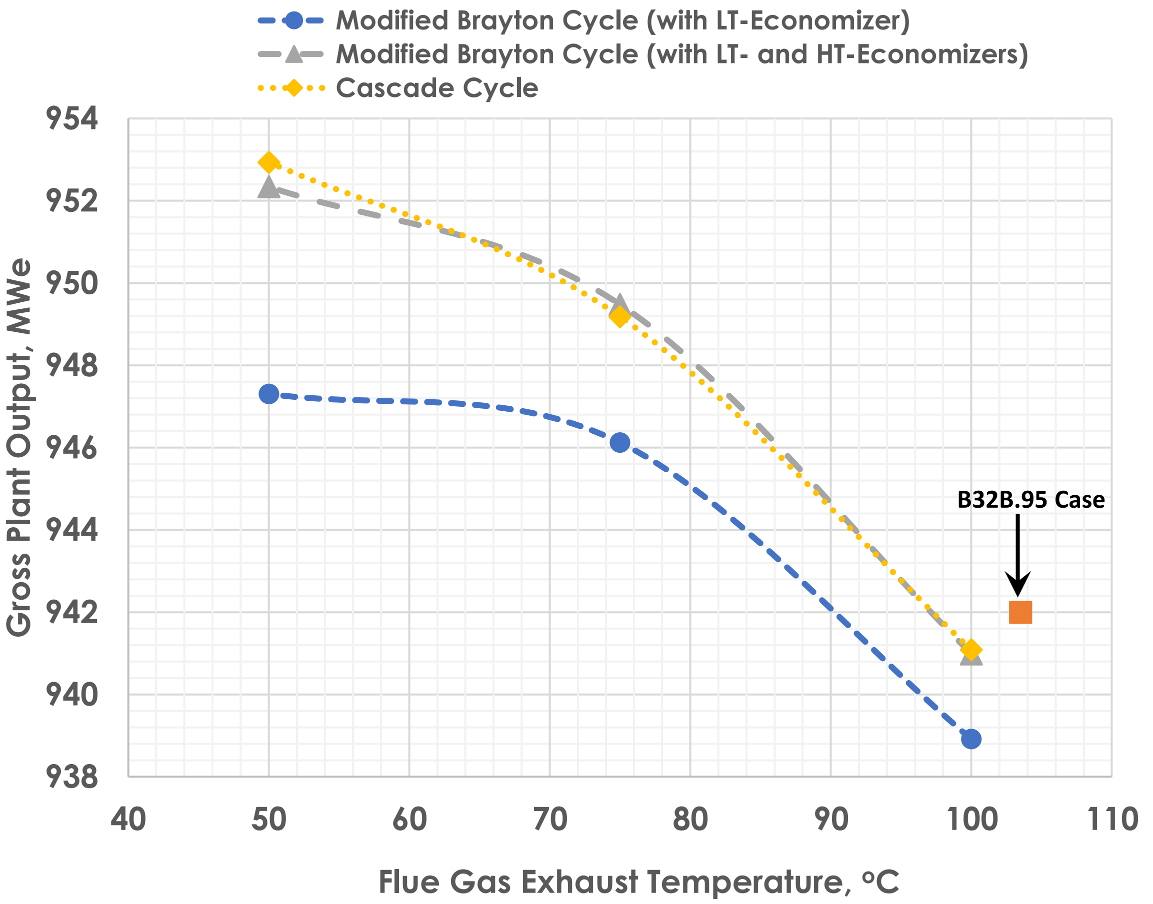
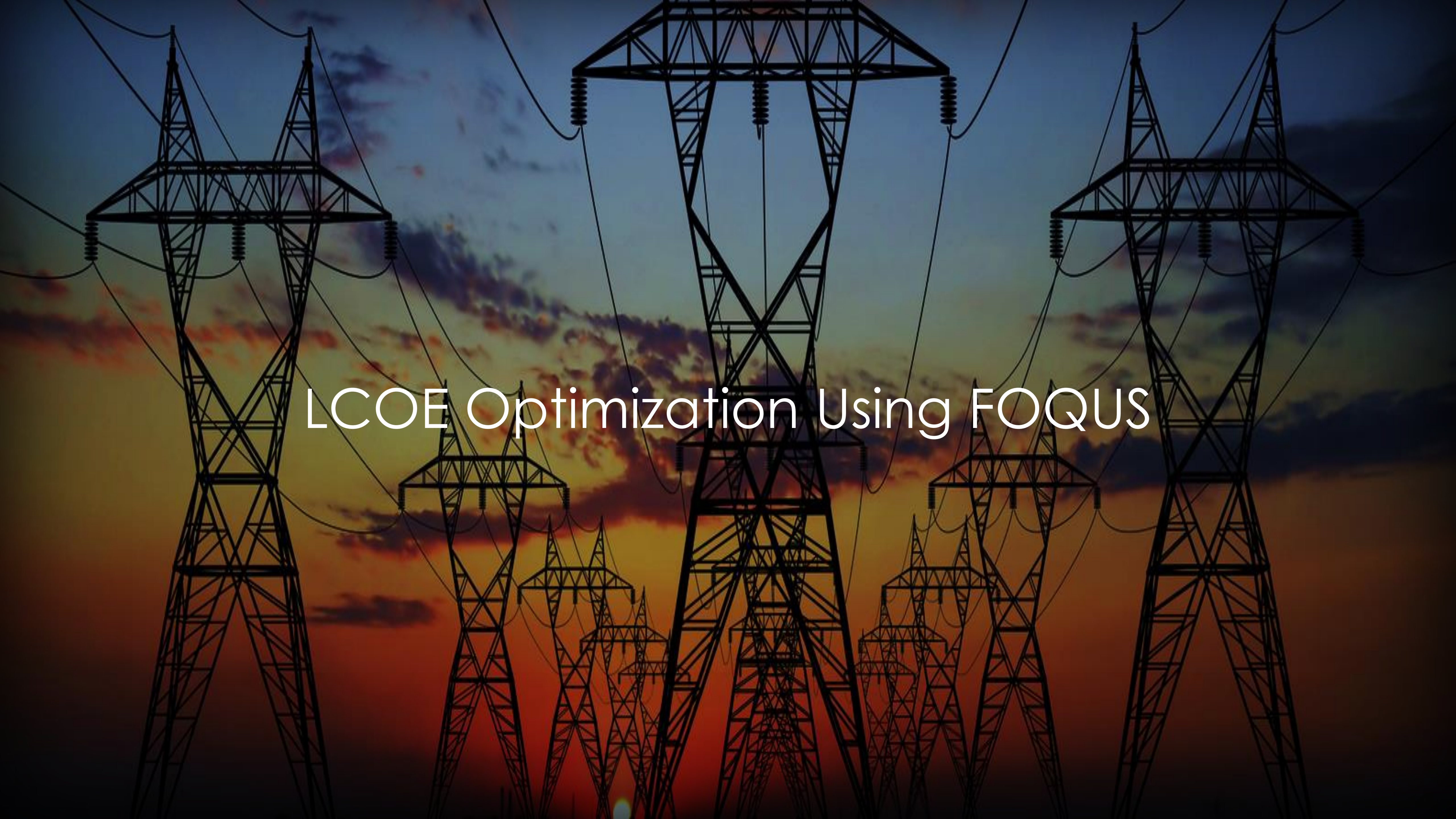
- Spreadsheet models were used to maximize power output for each of the configuration as a function of flue gas exhaust temperature
- sCO_2 cycles lead to more effective heat recovery from flue gas and sCO_2 turbine exhaust than reference plant (B32B.95 Case)

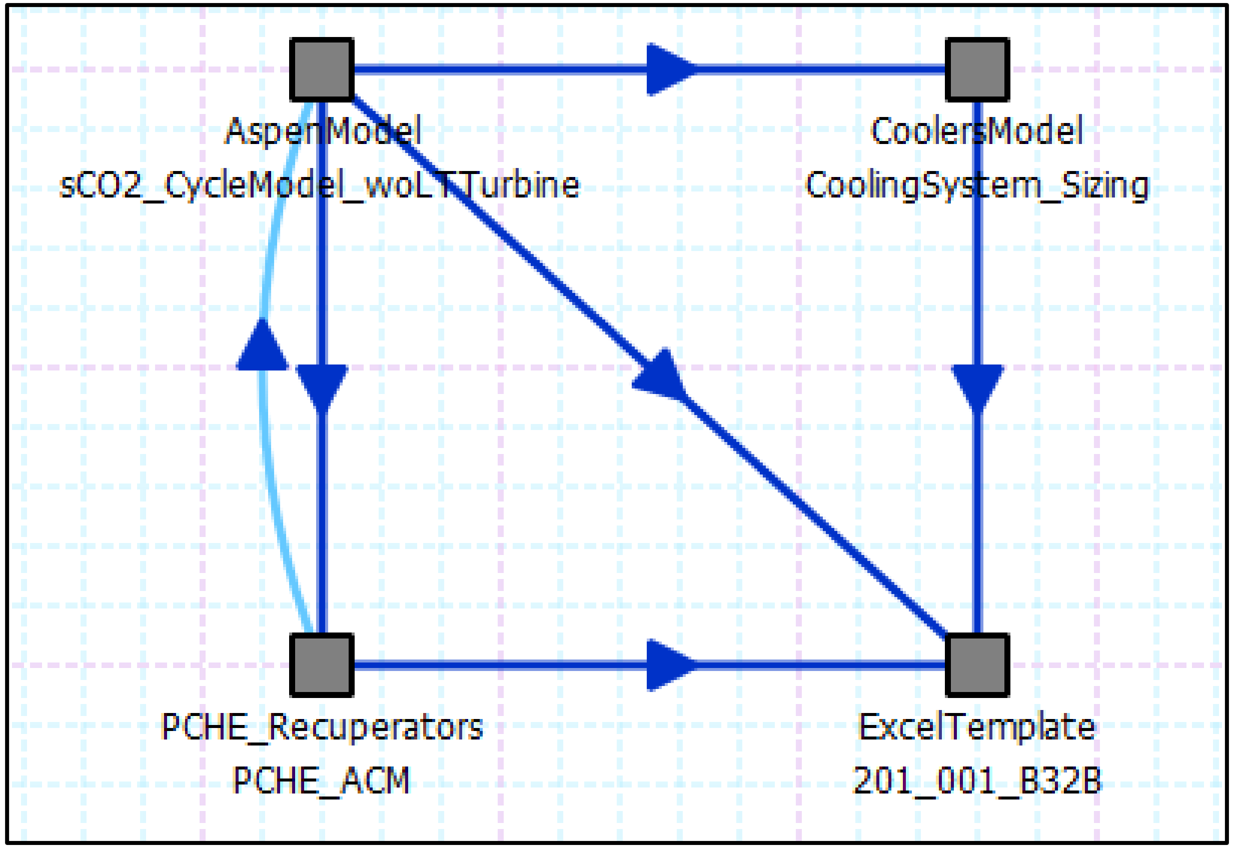


LCOE Optimization Using FOQUS



NETL Software FOQUS Used for Optimization

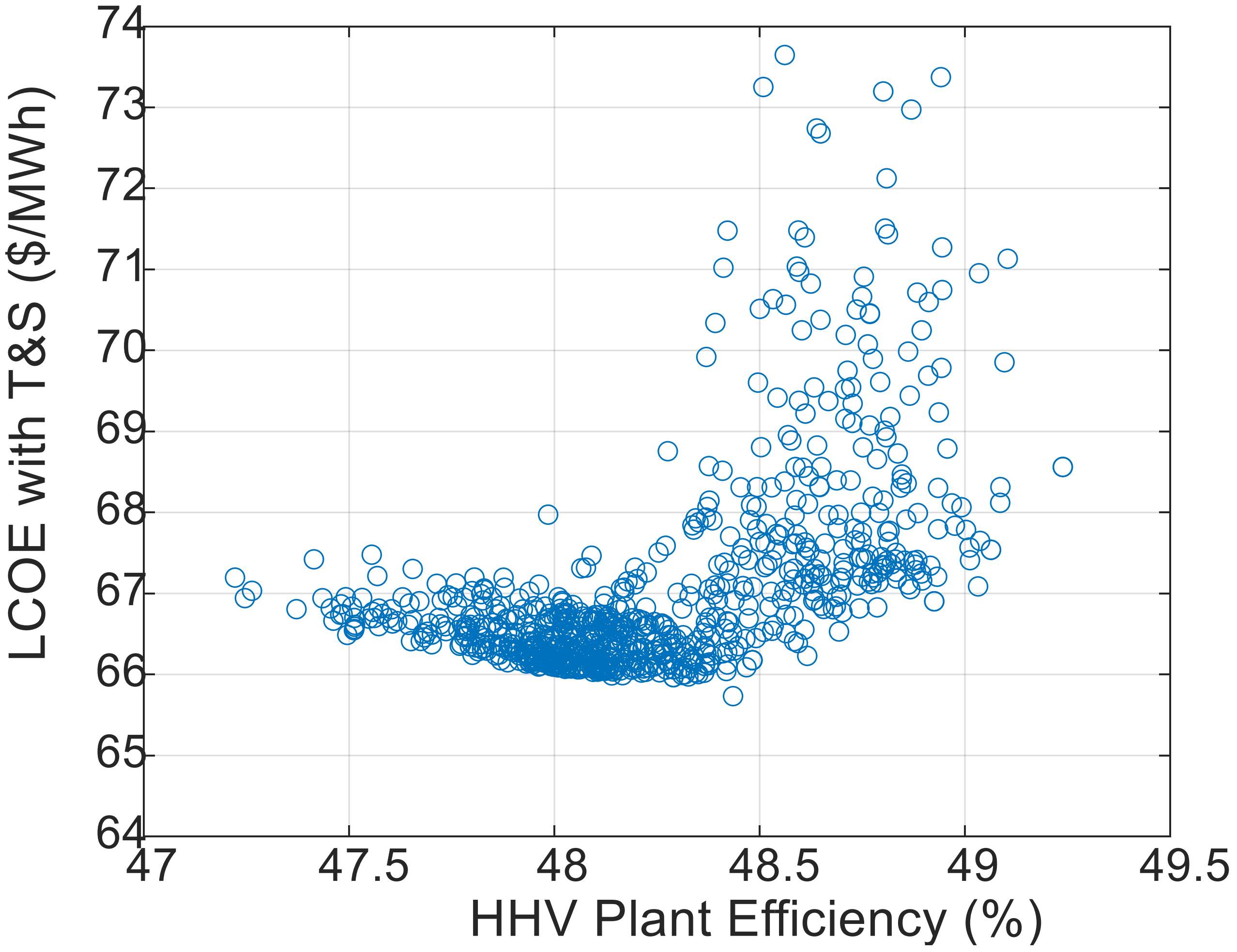
- Final FOQUS model includes four nodes
  - Plant Aspen model
    - Single model for all the sCO_2 cycle configurations
  - PCHE ACM models
    - Calculates HTR, LTR mass
  - Adiabatic Cooler system Excel model
    - Calculates cooling system aux power, water consumption rate and total cost
    - Midwest 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, °C	537.0	563.5	587.1
Cooler outlet temperature	T_{cooler}, °C	18.8	20.6	21.6
Cycle max pressure	P_{max}, MPa	30.1	30.6	27.7
HTR approach temperature	$T_{App,HTR}$, °C	60.0	15.0	13.0
PHX approach temperature	$T_{App,PHX}$, °C	7.3	9.0	15.0
LTR approach temperature	$T_{App,LTR}$, °C	6.4	6.8	7.5
LT-Econ approach temperature	$T_{App,LT-Econ}$, °C	2.8	6.2	4.0
HT-Econ heat duty	$Q_{HT-Econ}$, MW	N/A	129.1	215.6
PHX heat duty	Q_{PHX}, MW	470.1	362.9	276.4
HTR total pressure drop	ΔP_{HTR}, bar	3.2	2.9	1.9
LTR total pressure drop	ΔP_{LTR}, bar	1.2	1.2	2.2
Main cooler pressure drop	ΔP_{MC}, bar	0.049	0.045	0.049
Compressor intercooler pressure drop	ΔP_{MCIC}, bar	0.5	1.2	1.1
Flow split fraction to LT turbine	X_{LT}	N/A	N/A	20.6%

Ambient Temperature = 15°

Performance and Economic Comparison (Optimized Cases)

Performance Summary

- sCO_2 power cycles have slightly lower plant efficiency
  - Feedwater/condensate pumps are not needed for the sCO_2 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_2/Steam Power Cycle, MWe	256.0	245.0	242.0	241.0
Total Gross Power, MWe	**942.0**	**931.0**	**927.0**	**926.0**
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_2 Capture/Removal Auxiliaries, kWe	19,200	19,200	19,200	19,200
CO_2 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_2/Steam Turbine Auxiliaries	230	230	230	230
Transformer Losses, kWe	3,020	2,970	2,960	2,950
Total Auxiliaries, MWe	**65**	**58**	**58**	**57**
Net Power, MWe	**877**	**873**	**869**	**868**
Net Plant (HHV) Efficiency (%)	48.7%	48.4%	48.2%	48.2%
Combustion Turbine (HHV) Efficiency, %	38.0%	38.0%	38.0%	38.0%
Raw water consumption, gpm/MW_{net}	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

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- sCO_2 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
  - Flue gas cleanup costs are lower due to reduced volumetric flowrate (lower temperature and density)
- 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
Capital Costs (TPC, $/1000)				
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_2 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
Total	**$1,429,961**	**$1,404,649**	**$1,426,415**	**$1,445,204**
Total, $/kWe	**$1,630**	**$1,610**	**$1,641**	**$1,665**

sCO_2 Power Cycle Cost Breakdown

- sCO_2 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

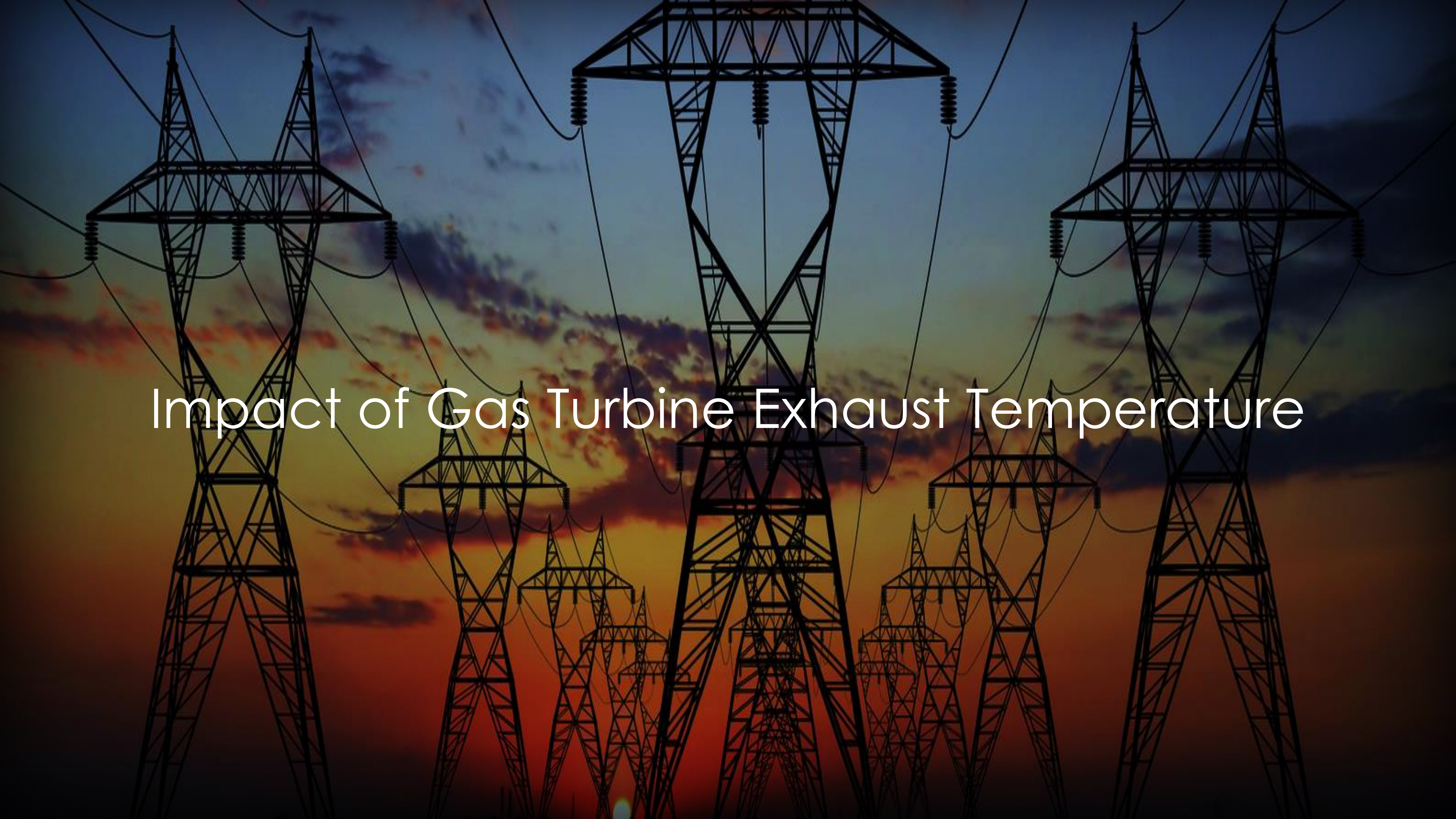
Cost Account Description	Modified Brayton (LT-Econ)	Modified Brayton (LT-and HT-Econ)	Cascade Cycle
Capital Costs (TPC, $/1000)			
Main CO_2 Compressor	$11,716	$11,699	$11,817
High Temperature Recuperator	$16,047	$19,206	$29,929
Low Temperature Recuperator	$26,719	$21,061	$20,261
Adiabatic Coolers	$77,212	$70,885	$73,296
CO_2 Turbine	$11,926	$11,989	$14,834
Piping System	$12,703	$12,703	$12,703
System Foundations	$4,543	$4,496	$4,475
Total	**$160,351**	**$152,039**	**$167,315**
Total, $/kWe	**$184**	**$175**	**$193**

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
LCOE ($/MWh)				
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
Total (Excluding T&S)	**62.4**	**62.1**	**62.8**	**63.3**
CO_2 T&S	3.6	3.6	3.6	3.6
Total (Including T&S)	**66.0**	**65.7**	**66.4**	**66.9**

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°C
Combustion Turbine Power, MWe	686.0	686.0	692.0
sCO_2/Steam Power Cycle, MWe	256.0	245.0	256.0
Total Gross Power, MWe	**942.0**	**931.0**	**948.0**
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_2 Capture/Removal Auxiliaries, kWe	19,200	19,200	19,200
CO_2 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_2/Steam Turbine Auxiliaries	230	230	230
Transformer Losses, kWe	3,020	2,970	3,020
Total Auxiliaries, MWe	**65**	**58**	**59**
Net Power, MWe	**877**	**873**	**889**
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

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- 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
LCOE ($/MWh)			
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
Total (Excluding T&S)	***62.4***	***62.1***	***61.7***
CO_2 T&S	3.6	3.6	3.5
Total (Including T&S)	***66.0***	***65.7***	***65.2***

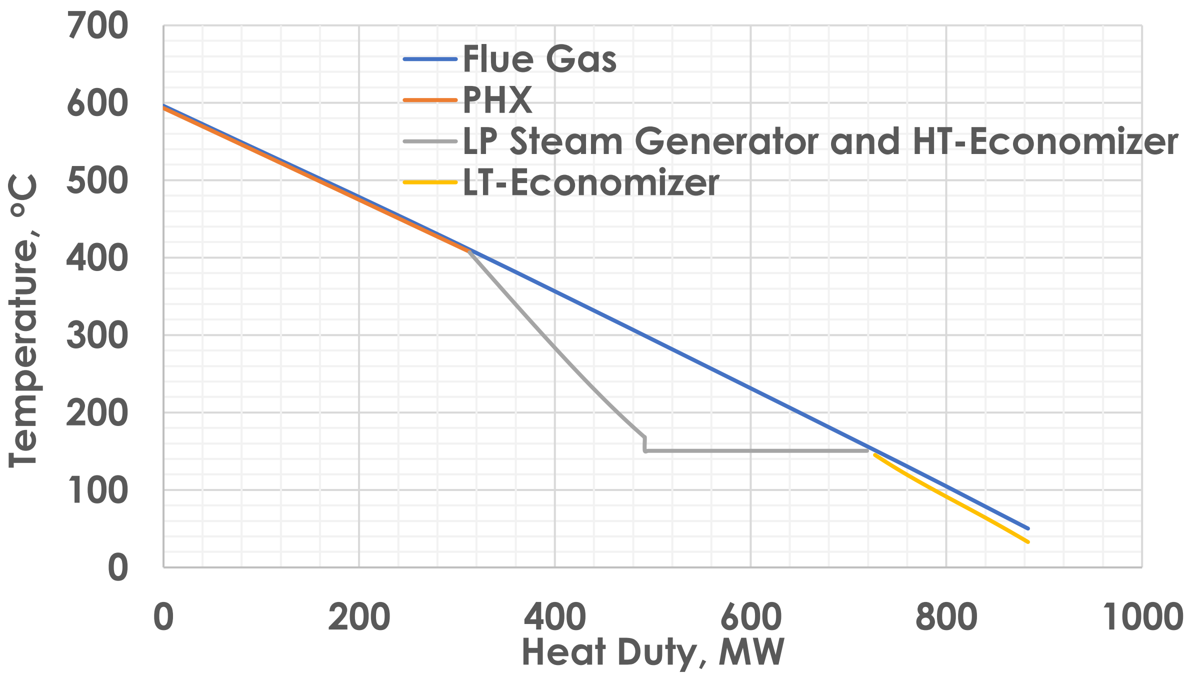
Conclusions and Further Recommendations

Conclusions

- 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 sCO_2 turbine inlet temperature
  - Could reduce startup time and material fatigue
- Higher gas turbine exhaust temperature is needed for sCO_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°C which limits the sCO_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 sCO_2 be used as heat source for solvent regeneration?
  - Plan to conduct a thermodynamic evaluation of the concept



Acknowledgments

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Questions/ Comments

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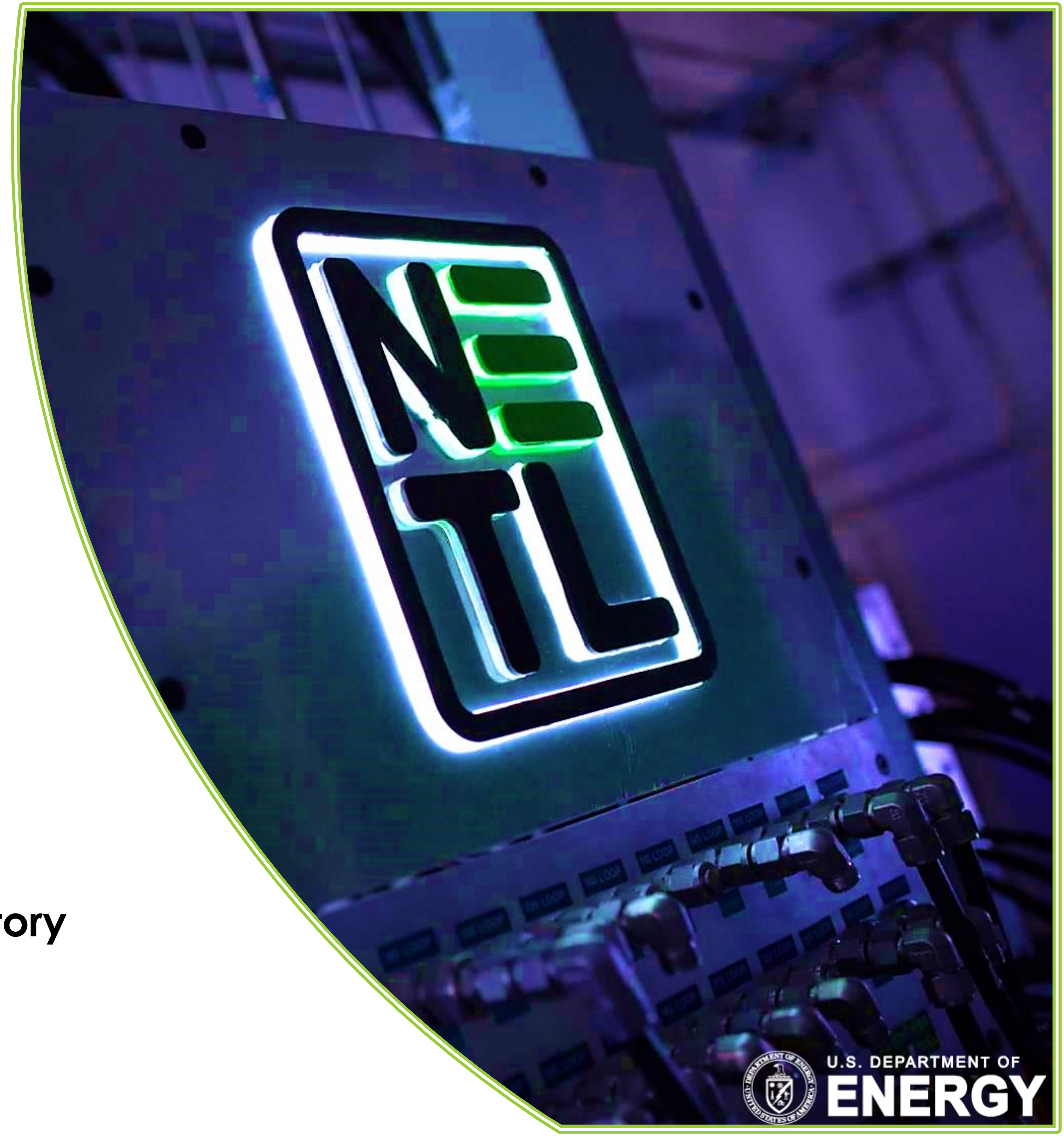

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Extra Slides

Economic Assumptions

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- Capital costs for the sCO_2 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_2 transportation and storage (T&S) cost is assumed to be $10/tonne CO_2 (from Midwest to Illinois Basin)
- The Aspen model and Excel templates will be subjected to QA/QC