Preliminary Cost and Performance Results for a Natural Gas-fired Direct sCO_2 Power Plant

NATIONAL ENERGY TECHNOLOGY LABORATORY

Charles W. White, Nathan T. Weiland

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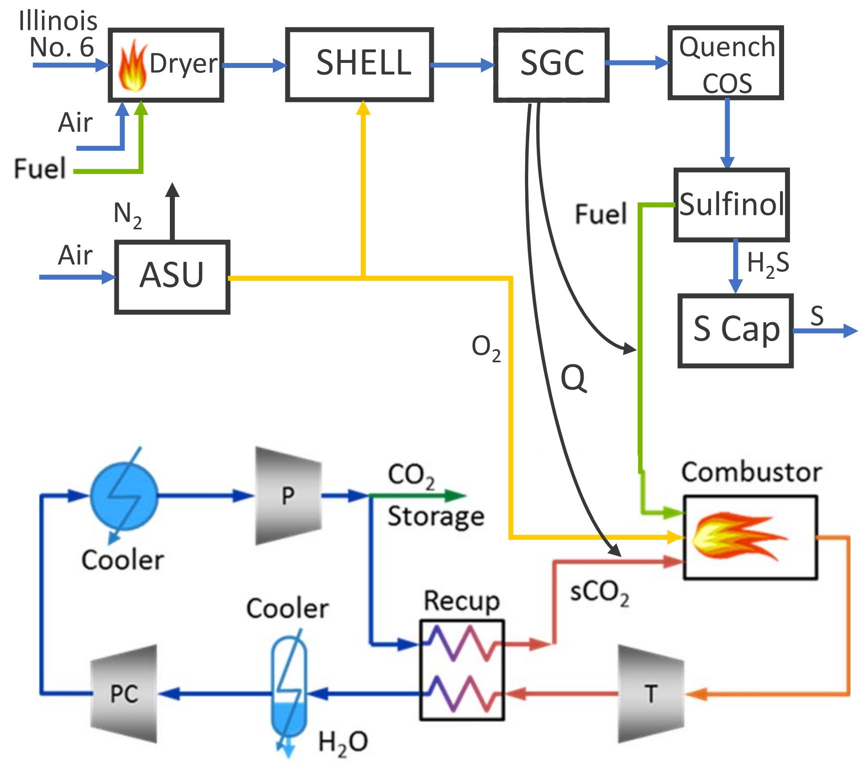
Technology Overview – Direct sCO_2 Cycles

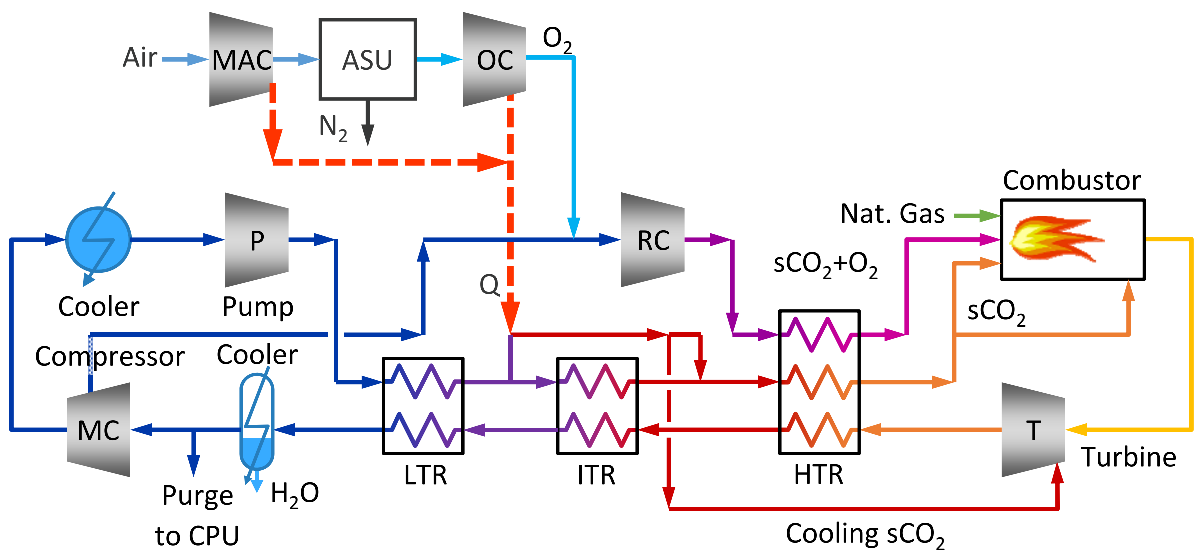
Characteristics and Benefits

- **Direct combustion of fuels (NG, coal-derived syngas) and oxygen in sCO_2 working fluid**
  - sCO_2 and water from combustion expanded in turbine to generate power
- **Moderate pressure ratio (8-10), relatively high turbine inlet temperatures (T_{in} = 1200 °C)**
  - Cycle limited by recuperator inlet temperature at turbine exhaust, requires expensive alloys to achieve higher TIT
- **Recuperation of heat to sCO_2 recycled to the combustor significantly improves efficiency**
- **High purity CO_2 purge stream ready for storage or EOR**
  - Near-complete carbon capture at storage pressure
- **Low or no water consumption**
  - Water condensed from the primarily sCO_2 exhaust
  - Water producing cycle if dry cooling is used



Analysis of Natural Gas Direct-Fired sCO_2 Power Cycle

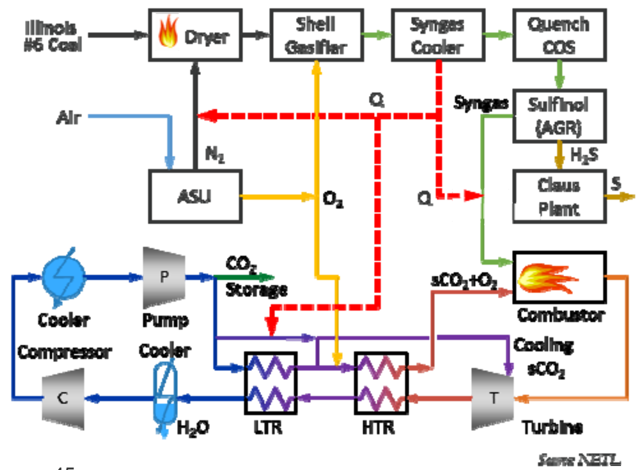
- <u>Objective</u>: Determine whether a natural gas-fired direct sCO_2 plant can compete economically against a natural gas combined cycle (NGCC) plant with carbon capture and storage (CCS)
- <u>Approach</u>: Develop a performance and cost baseline for a NG-fired direct sCO_2 cycle
- NG-direct sCO_2 plant design:
  - Low pressure cryogenic Air Separation Unit (ASU) with 99.5% oxygen purity
  - Thermal integration between sCO_2 cycle, ASU, and O_2 compressor enabled by 3 stage recuperation train
  - Oxy-NG Combustor
  - Cooled sCO_2 turbine
  - Condensing sCO_2 cycle operation
  - CO_2 purification unit (CPU) required to meet CO_2 pipeline purity specs

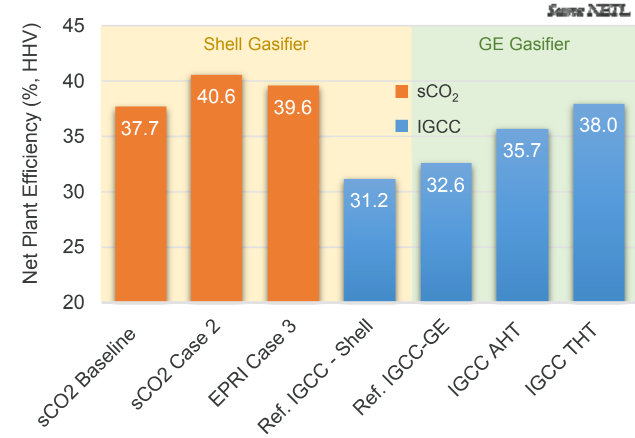


Background

NETL's Integrated Gasification Direct sCO_2 Cycle Study[1,2]

- **Modeled two thermally-integrated Shell gasifier/ direct sCO_2 plants with carbon capture[1,2]**
  - Net plant thermal efficiency of 40.6% (HHV) with 99% carbon capture
  - 20% Cost of Electricity (COE) improvement over Shell IGCC system with carbon capture, mostly due to higher thermal efficiency
- **Future gasification/direct sCO_2 analyses will consider different gasifier types and/or syngas cleanup strategies to improve plant efficiency**
  - Catalytic gasification, GE quench and radiant gasifiers
  - In-situ syngas cleanup (i.e. 8 Rivers' approach) may improve efficiency to ~44%



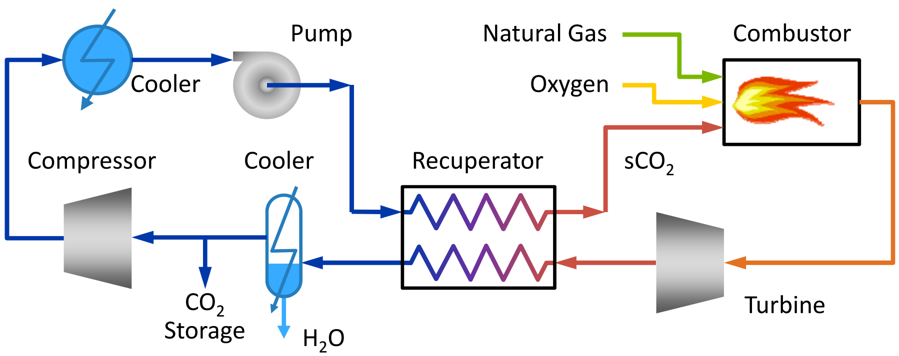


[1] Weiland, N.T., Shelton, W., Shultz. T., White, C.W., and Gray, D. "Performance and Cost Assessment of a Coal Gasification Power Plant Integrated with a Direct-Fired sCO2 Brayton Cycle," Report: NETL-PUB-21435, 2017.
[2] Weiland, N.T., and White, C.W., "Techno-economic Analysis of an Integrated Gasification Direct-Fired Supercritical CO2 Power Cycle," *Fuel*, **212**:613-625, 2018.

Methodology

Direct-fired sCO_2 Power Cycle Performance Estimation

- **System models for each case created using Aspen Plus®**
- **Steady-state lumped parameter models**
- **Physical property methods:**
  - LK-PLOCK for sCO_2 power cycle
  - PENG-ROB for BOP
- **When possible, Aspen models tuned to vendor performance data**
- **sCO_2 power cycle unit operations based on performance targets and discussions with turbomachinery and HX vendors**

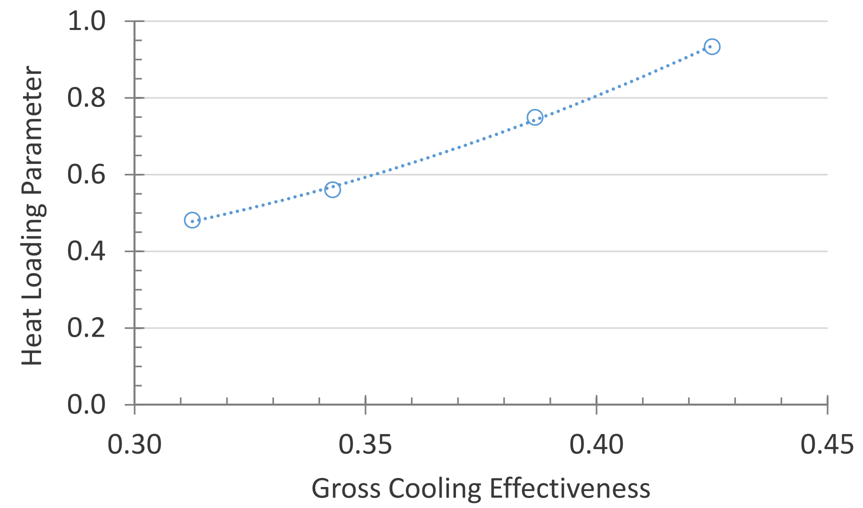


Section	Parameter	Baseline sCO_2 Cycle
Combustor	O_2 purity	99.5%
	Excess O_2	1%
	Pressure drop	689 kPa (100 psid)
	Heat loss	Zero
Turbine	Inlet temp	1204 °C (2200 °F)
	P_{inlet}	30.0 MPa
	PR, P_{exit}	10.2, 2.94 MPa
	Blade cooling	4.7%
Recuperator	Max temp	760 °C (1400 °F)
	Min T_{app}	10 °C (18 °F)
	Pressure Drop	0.14 Mpa (20 psid) per side
CO_2 Cooler	Cooler/condenser	26.7 °C (80 °F)
	Cooling source	Cooling tower
Recompression	CO_2 bypass	18.1%
Compressor	P_{inlet}	2.81 MPa
	P_{exit}	7.93 MPa
	Isentropic efficiency	85%
	Stages	4 (3 intercooled)
CO_2 Pump	P_{exit}	30.82 MPa
	Isentropic efficiency	85%
	Stages	2 (no intercooling)
CPU	Impurities	10 ppm O_2 max.

Turbine Cooling Methodology

Direct-fired sCO2 Power Cycle Performance Estimation

- **sCO_2 turbine model assumes 7 turbine stages and isentropic efficiency of 92.7%**
- **Turbine inlet temperature 1204 °C (2200 °F)**
- **Empirical turbine cooling model developed based on the NET Power cycle analysis in the IEAGHG study[3]**
  - Based on establishing a correlation between the Gross Cooling Effectiveness and a Heat Loading Parameter[4]
  - Correlation fit to variations in turbine cooling flow for turbine inlet temperatures of 1100 °C, 1150 °C, and 1200 °C from IEAGHG Study
  - Turbine coolant temperature of ≤ 400 °C
  - Assumes maximum blade metal temperature of 860 °C (T_{max})
- **Cooling bleed flow to stage *n* based on temperature of the stream entering the stage, T_n**
  - Ratio of cooling bleed at stage $n+1$ to the cooling bleed at stage n was set equal to $(T_{n+1} - T_{max}) / (T_n - T_{max})$



Gross Cooling Effectiveness = $(T_{gas} - T_{bulk\ metal}) / (T_{gas} - T_{coolant})$

Heat Loading Parameter = $(\dot{m}_{coolant}\ c_{p,coolant}) / (2\ H_{gas}\ A_{gas})$

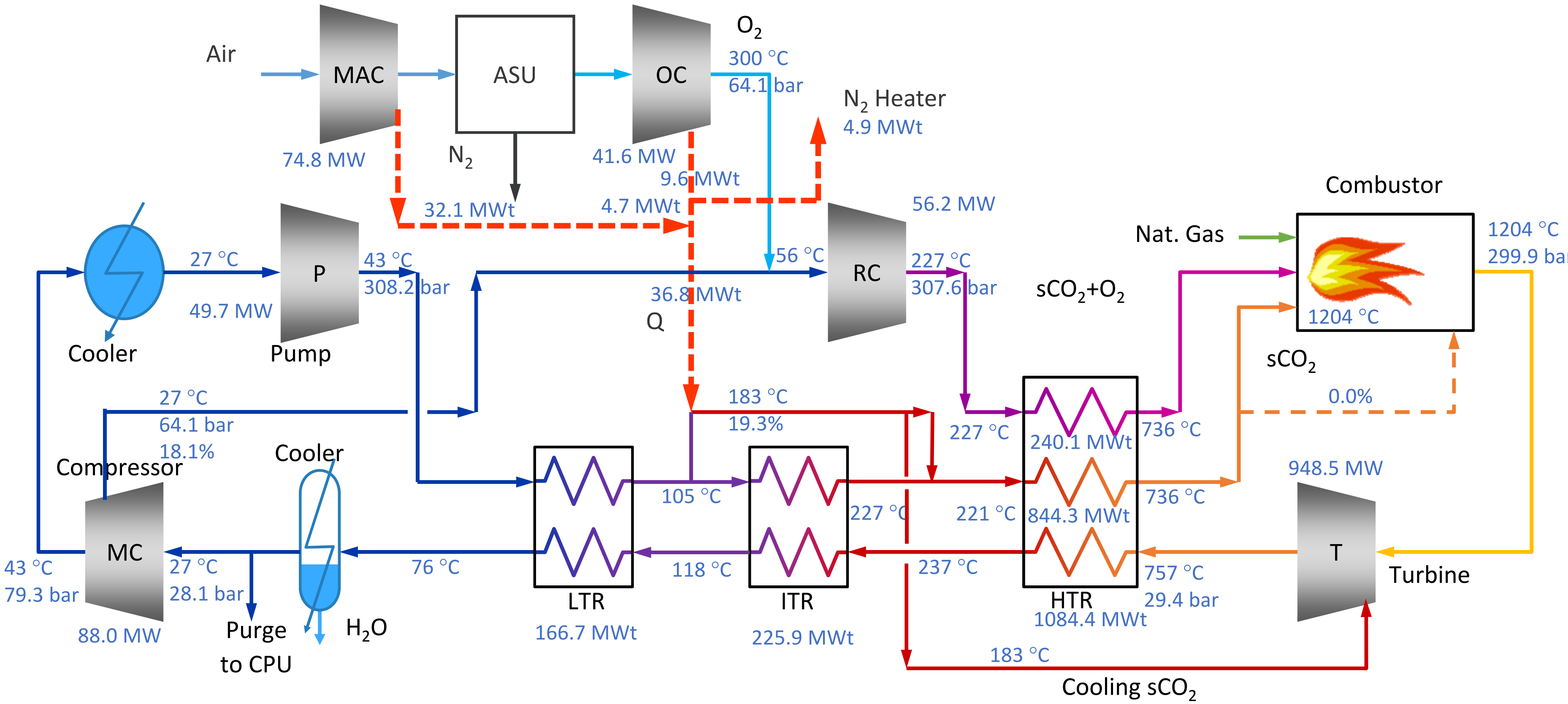
H_{gas} = average external gas heat transfer coefficient

A_{gas} = external gas/blade wetted surface area

[3] International Energy Agency Greenhouse Gas (IEAGHG), "Oxy-combustion Turbine Power Plants," Cheltenham, United Kingdom, August 2015.
[4] R. S. Bunker, Chapter 4.2.1: *Cooling Design Analysis*, Pittsburgh, PA: National Energy Technology Laboratory (NETL), 2006, pp. 295-309.

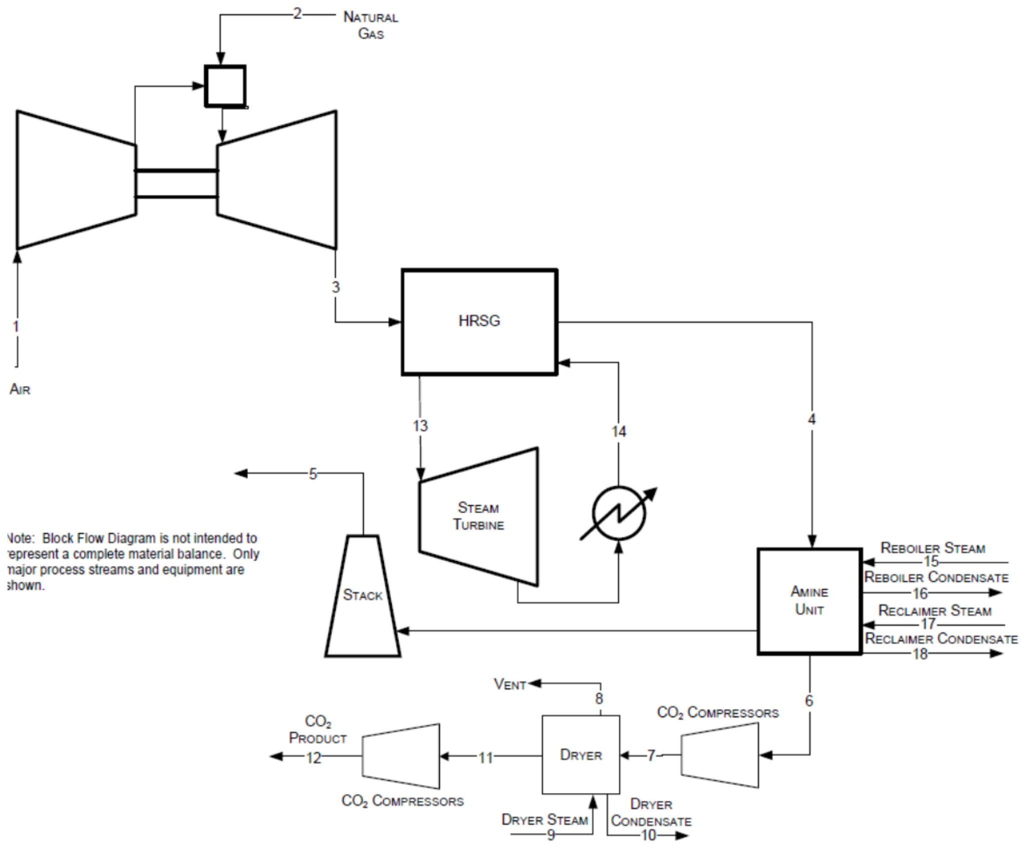
Baseline Natural Gas Direct sCO_2 Plant

Select State Point Data



Reference Plant Description

- **NGCC power plant with carbon capture and storage (CCS)**
  - From NETL Study: *Cost and Performance Baseline for Fossil Energy Plants*[5], Case B31B
  - State-of-the-art F-class turbine
    - Turbine inlet: 1371 °C (2500 °F)
  - Steam bottom cycle
    - 16.5 MPa/566°C/566°C
  - Amine unit for CO_2 removal
- **Differences:**
  - Requires CO_2 capture unit
  - 90% CO_2 capture



[5] National Energy Technology Laboratory (NETL), "*Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3*," NETL, Pittsburgh, July 2015.

Natural Gas Direct sCO_2 Performance

Baseline sCO_2 Compared to NGCC w/CCS

- sCO_2 plant produces an additional 31 MWe (6%) net power output for the same natural gas fuel input
- sCO_2 plant has large auxiliary power loads associated with the ASU and the sCO_2 Oxygen Compressor
- Overall sCO_2 plant auxiliary power requirement is 3.5 times higher than for the NGCC plant with CCS

Parameter	NGCC[5]	sCO_2 Cycle
Power Summary (MW)		
Combustion Turbine Power	428	949
Steam Turbine Power	182	---
CO_2 Pre-compressor Power	---	-88
CO_2 Pump Power	---	-50
CO_2 Recycle Compressor Power	---	-56
Generator Loss	-9	-16
Total Gross Power	**601**	**738**
Auxiliary Load Summary (MWe)		
ASU Main Air Compressor	---	74.8
Natural Gas Compressor	---	12.7
sCO_2 Oxygen Compressor	---	41.6
CO_2 Capture/Removal Auxiliaries	13.0	---
CPU & CO_2 Compression	15.0	8.7
Feedwater Pumps	3.6	---
Circulating Water Pumps	4.3	4.2
Cooling Tower Fans	2.2	2.2
Transformer Losses	1.8	2.6
Miscellaneous Balance of Plant	1.8	1.5
Total Auxiliaries	**42**	**148**
Net Power	**559**	**590**

[5] National Energy Technology Laboratory (NETL), "*Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3*," NETL, Pittsburgh, July 2015.

Natural Gas Direct sCO_2 Performance

Baseline sCO_2 Compared to NGCC w/CCS

- **sCO_2 plant achieves greater HHV efficiency, 48.2% vs. 45.7%, due to *cycle* efficiency differences**
- **sCO_2 plant captures more carbon (98.2%) than the NGCC plant**
  - NGCC limited to 90.7% carbon capture by amine process
- **sCO_2 plant consumes 17% less water**

Parameter	NGCC[5]	sCO_2 Cycle
Natural Gas Feed Flow, kg/hr	84,134	84,134
HHV Thermal Input, MW_{th}	1,223	1,223
LHV Thermal Input, MW_{th}	1,105	1,105
Total Gross Power, MW_e	601	738
Total Auxiliaries, MW_e	42	148
Total Net Power, MW_e	**559**	**590**
HHV Net Plant Efficiency, %	**45.7**	**48.2**
HHV CT/sCO_2 Cycle Efficiency, %	34.5	58.6
LHV Net Plant Efficiency, %	50.6	53.4
LHV CT/sCO_2 Cycle Efficiency, %	38.1	66.8
Steam Turbine Cycle Efficiency, %	43.5	---
Condenser/sCO_2 Cooler Duty, GJ/hr	888	1,978
Raw Water Withdrawal, $(m^3/min)/MW_{net}$	0.027	0.023
Raw Water Consumption, $(m^3/min)/MW_{net}$	0.020	0.016
Carbon Capture Fraction, %	**90.7**	**98.2**
Captured CO_2 Purity, mol%	99.93	100.00

[5] National Energy Technology Laboratory (NETL), "*Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3*," NETL, Pittsburgh, July 2015.

Natural Gas Direct sCO_2 Performance

Baseline sCO_2 Compared to Other NGCC w/CCS

- **sCO_2 plant performance compared to advanced NGCC plants**
  - NETL 2013 Report: *Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants*[6]
  - Considers larger gas turbine frame sizes, higher firing temperatures, and exhaust gas recirculation (EGR)
- **sCO_2 cycle between H-frame and J-frame NGCC cases, with higher carbon capture fraction**
- **Economic assumptions slightly different, thus Cost of Electricity (COE) is not compared**

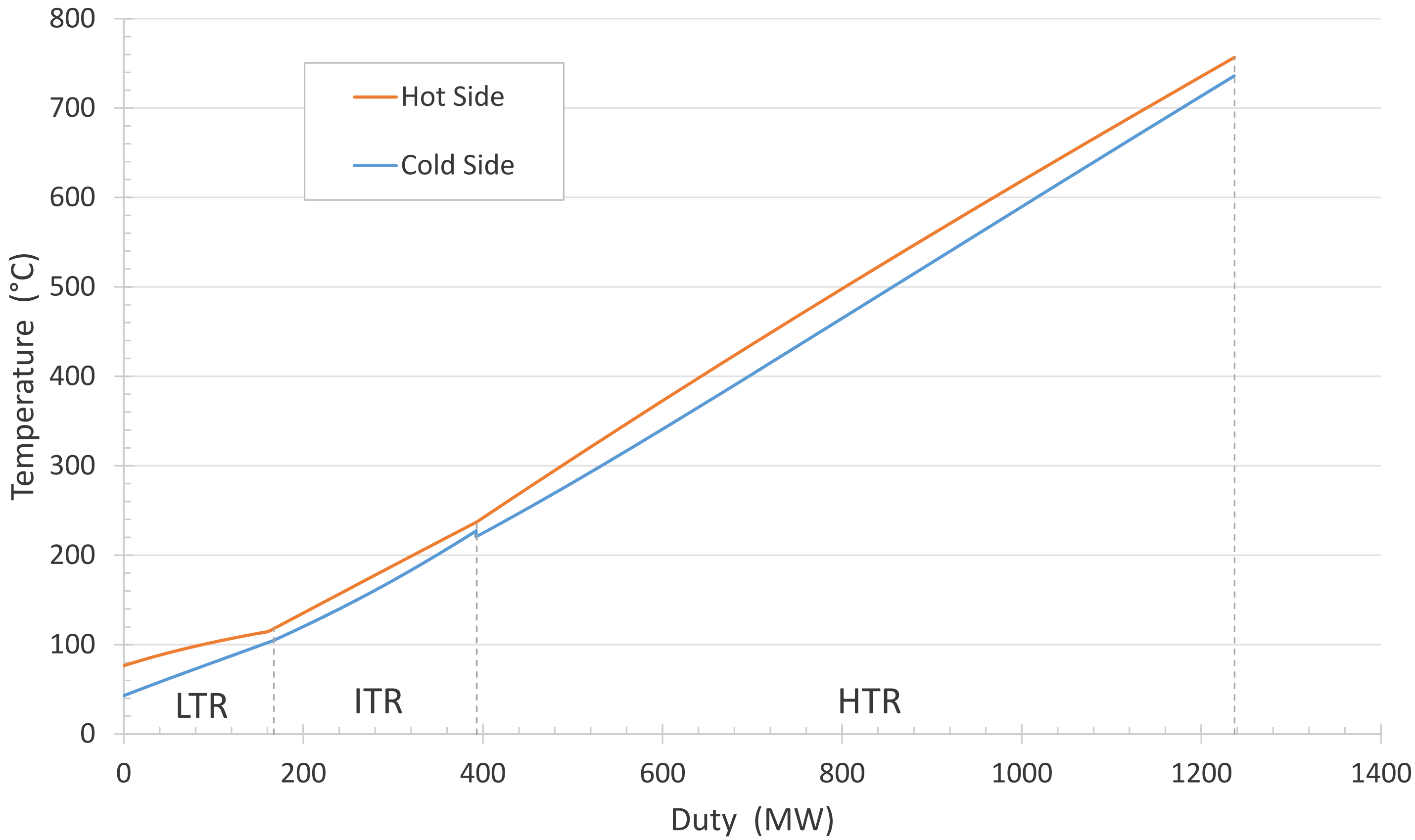
		NGCC Cases with CO_2 Capture[6]			
Parameter	sCO_2 Cycle	SOTA 7FA.05	SOTA 7FA.05 +EGR	SOTA H-frame	Adv. J-frame
Turbine Inlet Temperature, °C	1204	1359	1363	1487	1621
Turbine Pressure Ratio	10.2	17	17	20	23
HHV Thermal Input, MW_{th}	1223	1223	1233	1528	1737
Gas/sCO_2 Turbine Power, MWe	738	421	419	551	690
Steam Turbine Power, MWe	--	186	197	235	252
Total Auxiliaries, MWe	148	54	52	66	72
Total Net Power, MWe	**590**	**553**	**563**	**721**	**870**
HHV Net Plant Efficiency, %	**48.2**	**45.2**	**45.7**	**47.2**	**50.1**
Carbon Capture Fraction, %	**98.2**	**90.0**	**90.0**	**90.0**	**90.0**

[6] National Energy Technology Laboratory (NETL), "*Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants*," NETL, Pittsburgh, June 2013.

Natural Gas Direct sCO_2 Performance

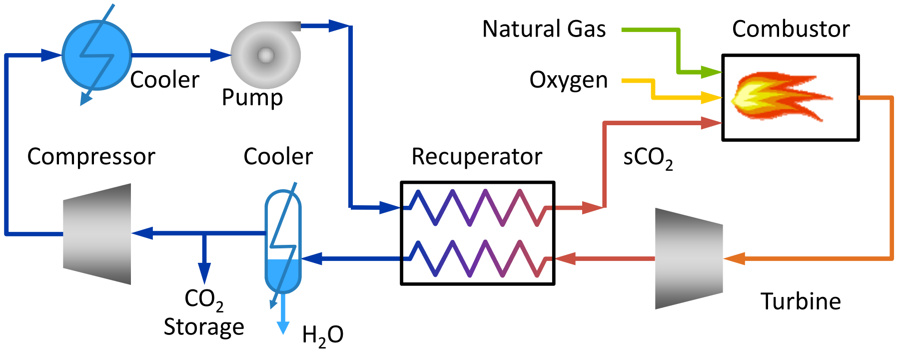
Recuperator T-Q Diagram

- Minimum $T_{approach}$ occurs at the hot end of the ITR
- Large $T_{approach}$ at the cold end of LTR due to water condensation on the hot side
- Average $T_{approach}$ just above 25 °C
- Average LMDT is a little below 18 °C

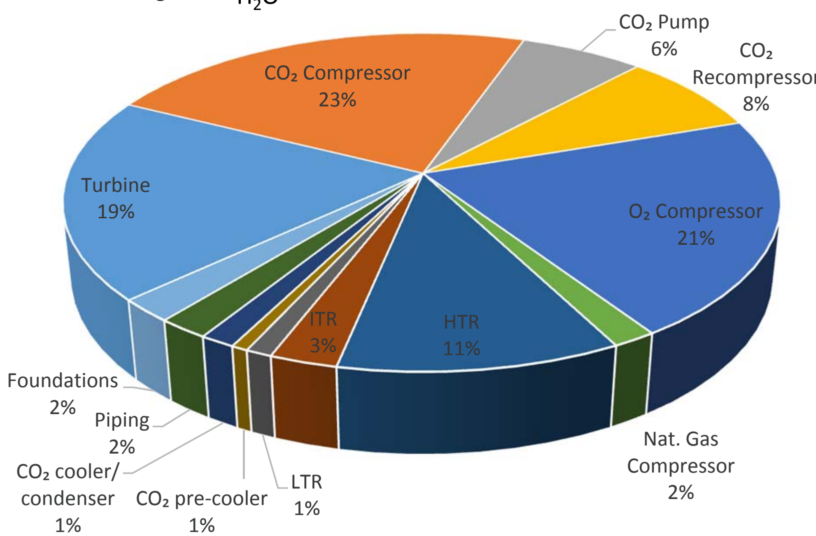


Methodology – Economic Analysis

sCO2 Power Cycle Component Capital Cost Estimation



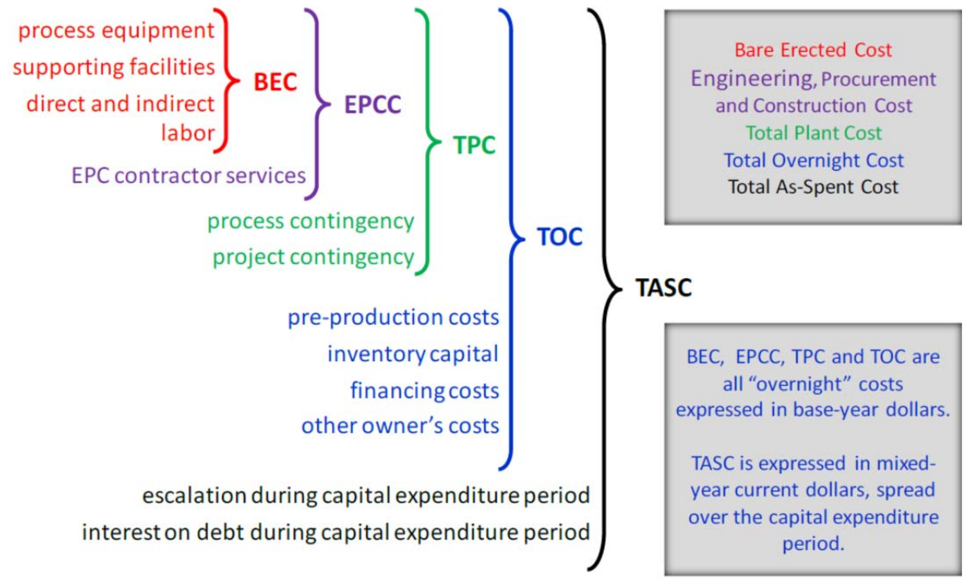
- **Oxy-combustor Turbine**
  - Assumes inner and outer casings, similar to Toshiba's design
  - Outer casing based cost for a similarly-sized HP steam turbine
  - Balance of turbine and combustor analogous to conventional gas turbine without compressor (-18%)
- **sCO_2 Recuperators and Coolers**
  - Based on vendor recuperator estimates for a utility-scale recompression sCO_2 cycle, adjusted for total duty and driving force
  - For CO_2 coolers, LTR, and ITR: $0.294/(W/K)
  - For HTR, assume two units with different materials, installed in series:
    - For hot side temperature < 600 °C: $0.253/(W/K)
    - For hot side temperature > 600 °C: $1.318/(W/K)
  - Economic sensitivity to recuperator specific costs performed
- **Compressor and Pump**
  - Based on vendor quote data for the main and bypass compressors for a utility-scale recompression Brayton sCO_2 cycle
  - Scaling algorithm divides the equipment cost into required power (60%), inlet volumetric flow rate (20%), and inlet temperature (20%)
  - New compressor scaling algorithm under development



Methodology – Economic Analysis

Standardized NETL Economic Analysis Methodology[7]

- **Capital Cost Estimation**
  - Costs estimated for a n^{th}-of-a-kind (NOAK) plant
  - Total Plant Cost includes estimated costs for equipment, installation, contractor fees, and contingencies Total overnight cost (TOC) calculated as sum of TPC and Owner's Costs
  - Typically -15% to +30% accuracy for NETL Baseline studies, but higher for this study due to early stage of direct sCO_2 technology
- **Operation and Maintenance (O&M) Costs**
  - Scaled based on cost algorithms used in coal gasification/direct sCO_2 study[1]
  - Assumptions:
    - Capacity Factor (CF) = 85%
    - Operating Labor = 6 operators/shift
    - Natural Gas Price = $6.13/MMBtu
- **Cost of Electricity (COE)**
  - TOC annualized using capital charge factor (CCF) assuming a 3 year construction period and 30 year operating lifetime
  - COE = sum of annualized capital cost, O&M costs, and T&S costs, normalized to net plant output ($/MWh)



$$\mathbf{COE} = \frac{\textit{First year capital charge} + \textit{First year fixed operating costs} + \textit{First year variable operating costs}}{\textit{Annual net megawatt hours of power generation}}$$

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

U.S. DEPARTMENT OF ENERGY

[1] Weiland, N.T., Shelton, W., Shultz. T., White, C.W., and Gray, D. "Performance and Cost Assessment of a Coal Gasification Power Plant Integrated with a Direct-Fired sCO2 Brayton Cycle," Report: NETL-PUB-21435, 2017.
[7] 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.

Baseline Direct sCO_2 Economic Analysis

Baseline sCO_2 Capital Costs Compared to NGCC w/CCS

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- **sCO_2 plant has 5 percent higher Total Overnight Cost (TOC) than reference NGCC plant**
  - 101% greater power island cost
  - 92% lower CO_2 capture/compression cost
  - 49% greater BOP costs
    - Primarily from the Accessory Electric Plant account
  - ASU is the largest-cost subsystem in sCO_2 plant
    - Combined cost of CO_2 Removal and Compression account and ASU is comparable to that of the NGCC plant
- **sCO_2 power cycle component costs**
  - Oxy-turbine (19%)
  - Compressors (58%)
  - Heat exchangers (19%)
  - Piping/foundations (4%)

Account	TPC, TOC ($1,000)	
	NGCC	sCO_2 Cycle
Total Plant Costs (TPC, $1,000)		
Feedwater & Misc. BOP Systems	57,936	36,403
Cryogenic ASU	0	342,954
CO_2 Removal & Compression	378,178	28,293
Combustion Turbine & Accessories	134,931	263,596
HRSG, Ducting, & Stack	50,316	0
Steam Turbine Generator	74,543	0
Cooling Water System	27,502	26,897
Accessory Electric Plant	59,813	107,393
Instrumentation & Control	19,568	41,861
Improvements to Site	11,987	13,207
Buildings & Structures	13,130	7,343
Total Plant Cost (TPC)	**827,904**	**867,945**
Owner's Costs and Total Overnight Costs ($1,000)		
Owner's Costs	180,477	188,034
Total Overnight Cost (TOC)	**1,008,381**	**1,055,979**

Baseline Direct sCO_2 Economic Analysis

Baseline sCO_2 COE Compared to NGCC w/CCS

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- **Only significant difference in O&M cost is the higher NGCC plant consumables cost due to the makeup need for CO_2 capture solvents**
- **sCO_2 plant shows an approximately 4% decrease in COE relative to the reference NGCC plant with CCS**
- **Savings in fuel and O&M costs for the more efficient sCO_2 plant offset the slight increase in TOC relative to the NGCC plant**
  - Spread over the expected 30-year lifetimes of the plants
- **However, findings from this economic analysis cannot be deemed definitive given the relatively large uncertainty inherent in the capital cost estimate**

O&M Cost Component		O&M ($1,000/yr)	
		NGCC	sCO_2 Cycle
Fixed O&M Costs	Labor	10,810	10,973
	Property Taxes & Insurance	16,558	17,359
	Total Fixed O&M Costs	**27,368**	**28,332**
Variable O&M Costs	Maintenance Material	8,679	9,098
	Consumables	7,821	2,578
	Total Variable Costs	**16,500**	**11,677**
Fuel Cost	**Natural Gas**	**190,913**	**190,913**
Total O&M Cost		**234,780**	**230,921**

COE Component	COE ($/MWh)	
	NGCC	sCO_2 Cycle
Capital Cost	26.9	26.7
Fixed O&M Costs	6.6	6.4
Variable O&M Costs	4.0	2.7
Fuel Cost	45.9	43.5
Total w/o T&S	**83.3**	**79.2**
T&S Cost	4.0	4.1
Total with T&S	**87.3**	**83.3**

Comparison with Other Studies

Plant Design and Performance Comparison

- **Efficiency of the system in this study is slightly low compared to thermal efficiencies obtained in other studies**
  - Primarily a result of the higher CO_2 capture fraction and purity
- **Specific power in this study is higher than other studies**
  - Specific Power = $Power_{Net\ Plant}$ / turbine exit flow
  - Increased Specific Power due to:
    - Higher pressure ratio
    - Higher turbine inlet temperature
    - Lower turbine cooling flow
  - Contributes to the lower specific plant cost relative to the IEAGHG and EPRI studies

Item	Units	This Study	8 Rivers Capital[8]	IEAGHG[9]	EPRI[10]	Scaccabarozzi et al[11]
Turbine Inlet Temp	°C	1204	1150	1150	1150	1127.7
Turbine Pressure Ratio		10.2	10	8.8	8.8	6.1
Turbine Cooling Flow	%	4.7		11.5	11.5	6.6
Turbine Coolant Temp	°C	183	<400	400	400	164
Thermal Input (HHV)	MWth	1223		1701	1374	851
Net Plant Power	MWe	590		846	664	425
Net Plant Efficiency	%, HHV	48.2	53.1	49.9	48.4	50.0
Specific Power	kJ/kg	334.2		300.0	290.8	267.4
CO_2 capture	%	98.2%	100.0%	90.0%	90.1%	
CO_2 purity	%	100%	94%	99.8%	99.6%	
Specific Plant Cost	$/kWe†	1471	~1000*	1651	1555	

†2011 dollar year basis; *target

[8] R. Allam, M. Palmer, G. J. Brown, J. Fetvedt, D. Freed, H. Nomoto, M. Itoh, N. Okita and C. Jones Jr., "High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating Atmospheric Emissions, Including Carbon Dioxide," *Energy Procedia,* **37**:1135-1149, 2013.
[9] International Energy Agency Greenhouse Gas (IEAGHG), "Oxy-combustion Turbine Power Plants," Cheltenham, United Kingdom, August 2015.
[10] Electric Power Research Institute (EPRI), "Oxy-Fired Coal and Natural Gas Power Plants – 2016 Detailed Feasibility Study," 3002008148, Palo Alto, CA, 2017.
[11] R. Scaccabarozzi, M. Gatti and E. Martelli, "Thermodynamic optimization and part-load analysis of the NET Power Cycle," *Energy Procedia,* **114**:551-560, 2017.

Sensitivity to Recuperator Cost Estimates

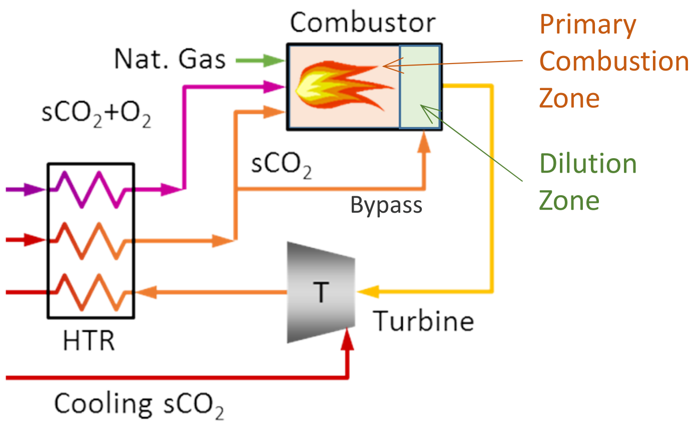
- **Recuperator cost estimates were based on the lowest of two proprietary vendor quotes**
  - LTR and HTR recuperators for a commercial-scale indirect-fired sCO_2 plant
- **Both vendors employed non-PCHE (printed circuit heat exchanger) microchannel recuperator designs**
- **Design approaches and cost estimates varied widely between the vendors**
- **Higher recuperator vendor estimate increases TPC by 8%, and COE (w/o T&S) by $2.9/MWh**
  - Illustrates effect of sCO_2 component cost uncertainty on utility-scale plant economics

Item	NGCC	sCO_2 Cycle	
		Vendor X	Vendor Y
Recuperator Specific Cost ($/(W/K))			
HTR (T > 600 °C)		1.318	3.274
HTR (T < 600 °C)		0.253	0.586
LTR, ITR, Coolers		0.294	0.440
Recuperator TPC ($1,000)			
HTR	---	23,880	78,106
ITR	---	5,739	8,600
LTR	---	2,236	3,351
Total Plant Cost ($1,000)	**827,904**	**867,945**	**939,363**
COE w/o T&S ($/MWh)	**83.3**	**79.2**	**82.1**
T&S Cost ($/MWh)	4.0	4.1	4.1
COE Total ($/MWh)	**87.3**	**83.3**	**86.1**

Sensitivity to Incomplete Combustion

Combustor Modeling Methodology

- **A simple incomplete combustion model was developed to determine its effect on cycle and plant performance**
  - Results thus far all assume complete combustion of natural gas and oxygen to combustion products
- **Modeled as CO production, which may result from:**
  - Incomplete fuel/air mixing or combustion instabilities
  - Slow combustion kinetics relative to combustor residence time
  - CO_2 dissociation at high flame temperatures
- **Feed to the combustor consists of four streams:**
  - Natural gas fuel
  - Preheated, oxygen/sCO_2 mixture with 30% oxygen by volume
  - Recycle sCO_2 flow to primary combustion zone
  - Recycle bypass sCO_2 flow to the combustor dilution zone



$$C_xH_y + (x/2 + y/4)\, O_2 \rightarrow x\, CO + y/2\, H_2O$$

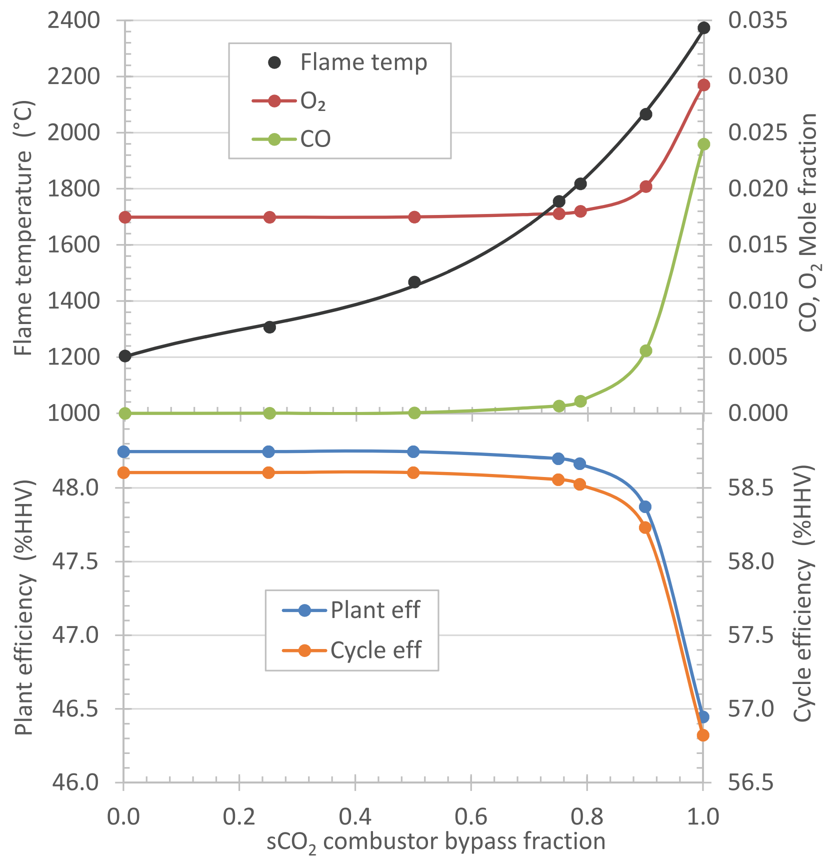
$$CO + ½\, O_2 \leftrightarrow CO_2$$

- **2-Stage Incomplete Combustion Model:**
  - Primary combustion zone:
    - Completely oxidizes fuel hydrogen content
    - Partially oxidizes fuel carbon content using the remaining oxygen to form $CO/O_2/CO_2$ equilibrium products
    - Temperature and equilibrium products represent average flame conditions
  - sCO_2 flow to the dilution stage simulates a quenching process with perfect mixing and no further chemical reactions occurring

Sensitivity to Incomplete Combustion

Combustor Flame Temperature & CO, O_2 Mole Fractions

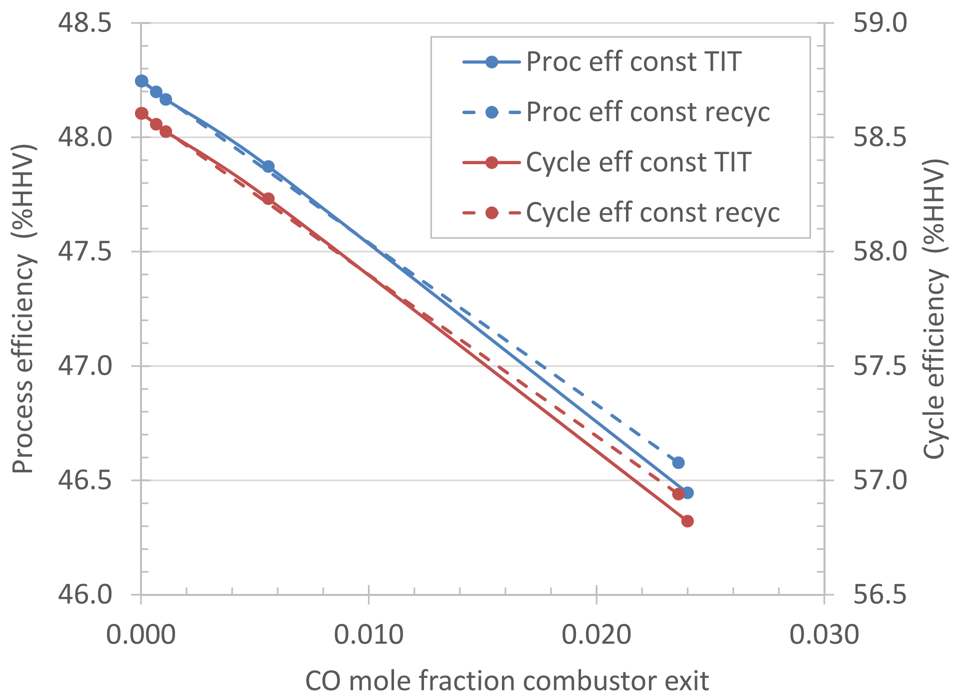
- **Impact of incomplete combustion on combustor and plant performance shown as the sCO_2 combustor diluent bypass fraction varies between 0 and 1**
- **The calculated adiabatic flame temperature rises with the bypass fraction**
    - Less sCO_2 dilution within the primary combustion zone
- **CO and O_2 mole fractions in the combustor effluent increase non-linearly with diluent bypass fraction**
- **At bypass fractions above 0.8, chemical equilibrium begins to favor larger amounts of O_2 and CO in the combustor products due to CO_2 dissociation at flame temperatures above about 1800 °C**
- **Little impact on process or cycle efficiency for bypass fractions below 0.8 (or $T_{flame} \leq 1800$ °C).**
- **As the bypass fraction increases beyond 0.8, the plant and cycle efficiency drop quickly**



Sensitivity to Incomplete Combustion

Process & Cycle Efficiency versus CO Mole Fraction

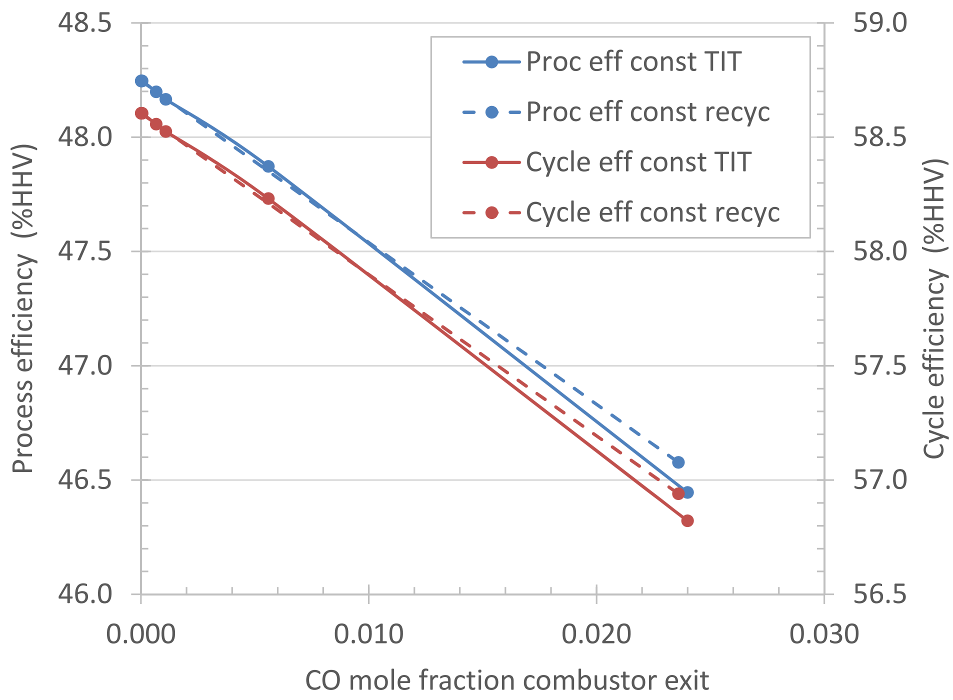
- **Plant and cycle efficiency have a roughly linear dependence on CO mole fraction**
  - Also accounts for effect of associated O_2 mole fraction from CO_2 dissociation
  - sCO_2 impurities decrease fluid density, increasing required compression power
- **Process and cycle efficiency drops by about 0.75 percentage points per mole percent of CO in the combustor exhaust**
- **Flame temperatures of 1600 – 1700 °C should be targeted for acceptable flame stability with minimal impact on plant efficiency**
  - This is a best-case scenario. Appropriate combustor design is still needed to ensure sufficient fuel/air mixing and residence time



Sensitivity to Incomplete Combustion

Conclusions

- CO_2 dissociation into CO and O_2 begins to occur for flame temperatures above about 1800 °C
- Effects are roughly the same whether a constant turbine inlet temperature (TIT) or constant sCO_2 recycle flow rate is targeted
- These results are applicable to any processes that may yield incomplete combustion, including chemical kinetics, flame quenching, incomplete fuel/ oxygen mixing, fuel/oxygen ratio fluctuations, etc.
- Points to the need for sCO_2 oxy-combustor design and modeling studies to ensure maximum conversion of fuel and oxygen to CO_2 in the combustion products



Baseline sCO_2 Techno-economic Analysis

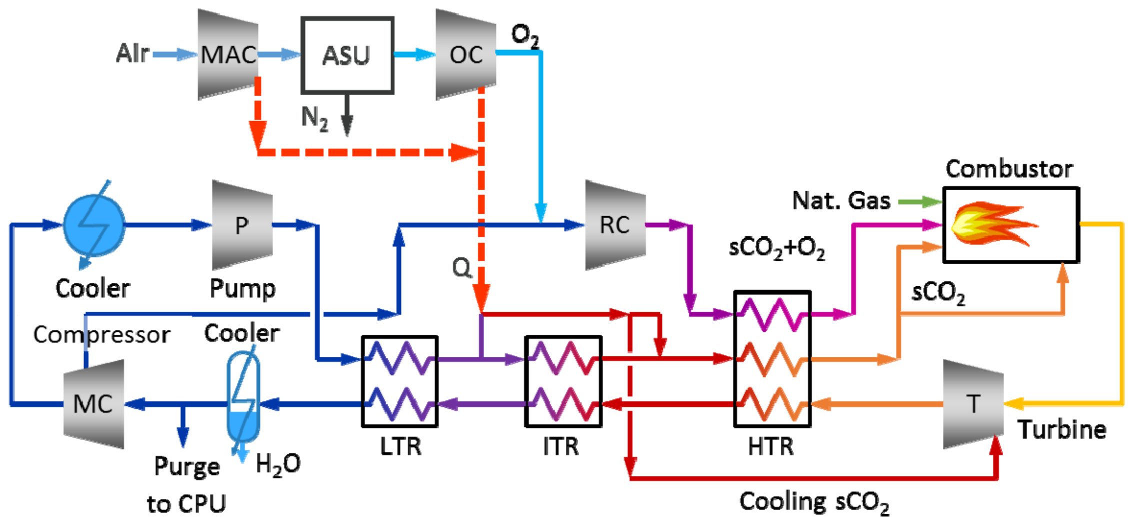
Conclusions

- **Plant design and performance is similar to other studies, but evolved organically out of the basic framework of direct sCO_2 power cycles and earlier work on coal-fueled direct sCO_2 power plants**
- **Baseline sCO_2 plant thermal efficiency of 48.2% (HHV) with 98.2% carbon capture**
  - Significant improvement over the reference NGCC plant with CCS, which has an efficiency of 45.7% and 90.7% carbon capture
- **The total plant cost for the baseline sCO_2 plant is comparable to the reference NGCC plant on a $/kW basis**
- **The increased fuel efficiency leads to a 3.6% lower COE for the sCO_2 plant, excluding CO_2 T&S costs**
- **Additional contributions of this work:**
  - A new model to determine sCO_2 turbine cooling flow requirements as a function of the coolant temperature
  - An incomplete combustion model to assess the effects of combustion-derived sCO_2 impurities on the overall performance of the plant
  - A component-level cost estimate for the plant
  - A COE calculation consistent with other NETL studies

Parameter	NGCC[5]	sCO_2 Cycle
HHV Thermal Input, MW_{th}	1,223	1,223
Total Gross Power, MW_e	601	738
Total Auxiliaries, MW_e	42	148
Total Net Power, MW_e	559	590
HHV Net Plant Efficiency, %	45.7	48.2
Carbon Capture Fraction, %	90.7	98.2
Captured CO_2 Purity, mol%	99.93	100.00
Total Plant Cost (TPC) ($1,000s)	1,008,381	1,055,979
Specific Total Plant Cost ($/kW)	1,481	1,471
COE w/o CO_2 T&S	83.3	79.2
COE with CO_2 T&S	87.3	83.3

Future Work

- The baseline sCO_2 plant design developed in this work will undergo further optimization and modification in future studies to develop a more cost-effective plant design
- Potential for efficiency improvement exists in implementing a high pressure ASU model in which the oxygen is pumped to high pressure as a liquid with low specific power, rather than compressing it as a gas in this study



- Future plans also include the development of control strategies and detailed component performance maps to enable evaluation of the part load and off-design capabilities of direct sCO_2 power cycles


Questions?

Presentation Outline

Master Page Subtitle 1

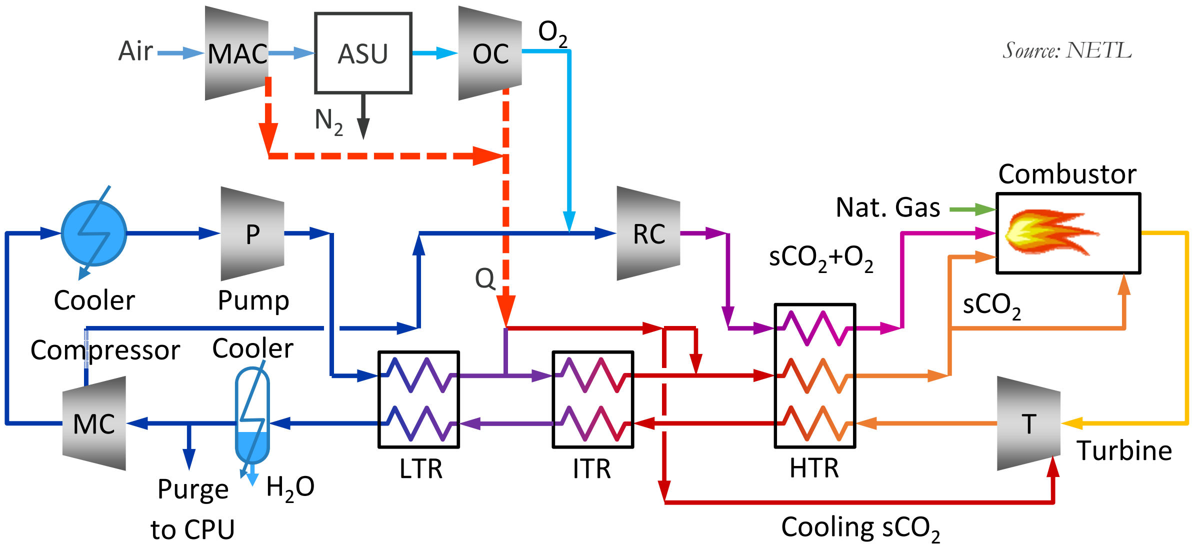
- **Background**
- **Methodology**
- **Baseline Direct-fired sCO_2 Plant**
  - Performance results
  - Economic Analysis results
- **Sensitivity Analyses**
  - Recuperator costs
  - Incomplete combustion
- **Comparison to Other Studies**
- **Conclusions**

Natural Gas Direct sCO_2 Cycle

Ongoing Techno-economic Analysis

- **LTR recovers heat of water condensation from hot side**
- **Oxygen compressor (OC) requires intercooling to limit O_2 to 300 °C max**
- **OC and MAC intercooling duties can be handled by an sCO_2 slip stream parallel to the ITR**
- **Recycle compressor draws fluid from internal stage of the main compressor**
  - Minimum flow set to yield max 30% O_2 in sCO_2+O_2 stream
- **Turbine Cooling sCO_2 flow rate dependent on TIT and coolant temperature**

- **sCO_2 plant HHV efficiency currently 48.2% *with* 99% carbon capture, with 3% lower COE than baseline NGCC plant with CCS (η_{HHV} = 45.7%)**
- **Changing O_2 compressor to a LOX pump may improve plant efficiency by ~3 percentage points**

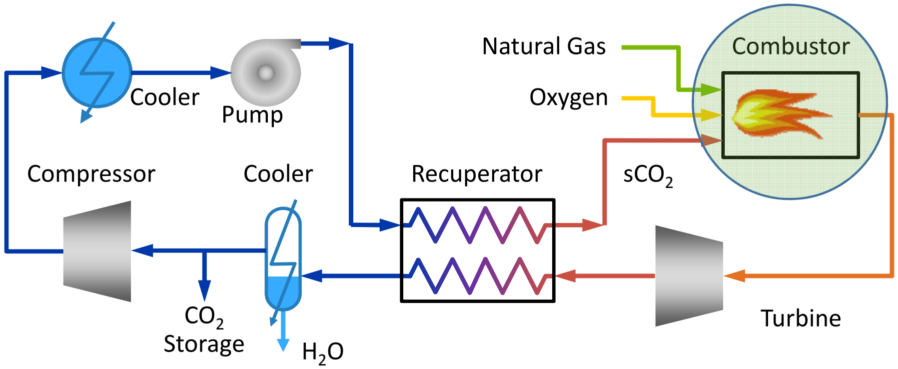


Source: NETL

Methodology

Direct-fired sCO_2 Power Cycle Performance Estimation – Oxy-combustor

- **Complete Combustion Model**
  - Series of combustion reactions for the oxidizable components of the fuel
  - Assumes 100% conversion of these fuel components
  - Excess oxygen calculated based on the fuel stream components entering the process
    - Oxidizable components in the recycle sCO_2 stream not used for excess oxygen calculation



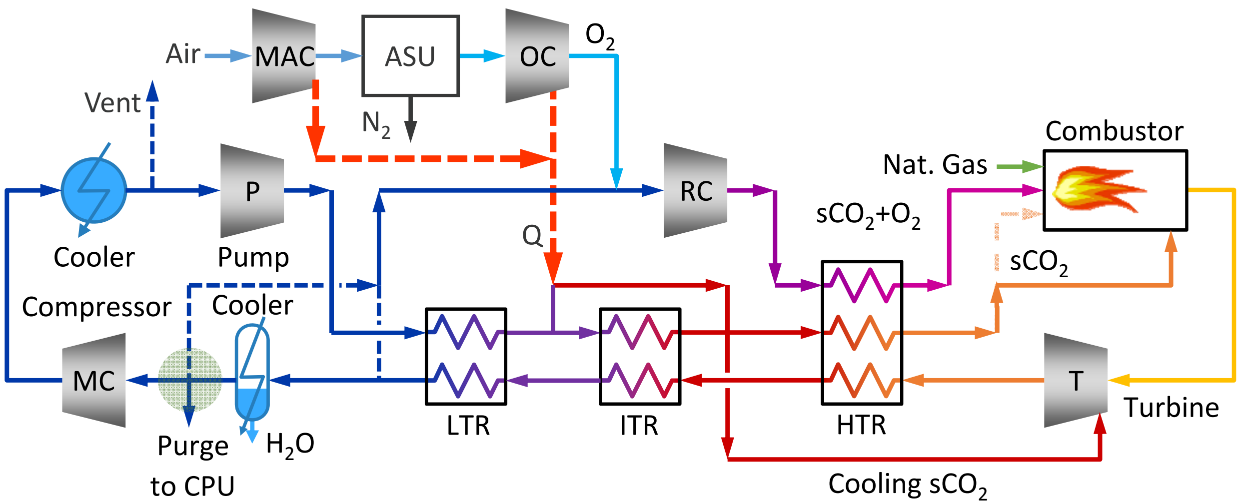
[1] International Energy Agency Greenhouse Gas (IEAGHG), "Oxy-combustion Turbine Power Plants," Cheltenham, United Kingdom, August 2015.

[2] R. S. Bunker, Chapter 4.2.1: Cooling Design Analysis, Pittsburgh, PA: National Energy Technology Laboratory (NETL), 2006, pp. 295-309.

Constant Recycle Flow Case

Process Description and Performance Results

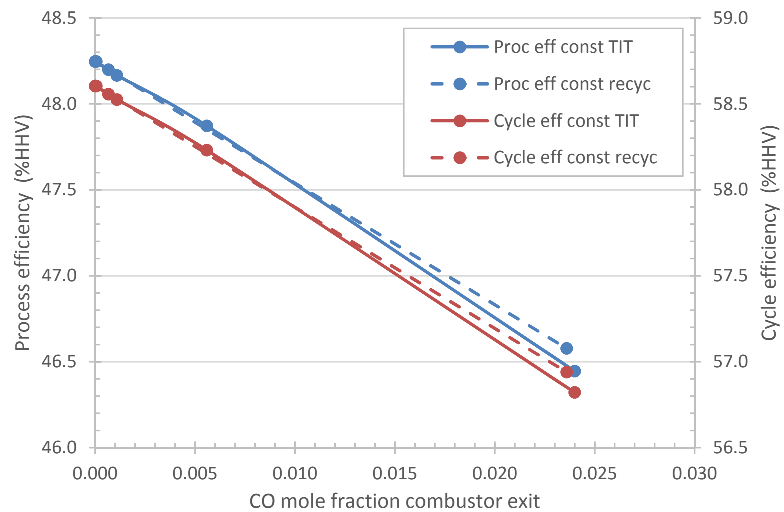
- **Alternative approach for controlling power cycle would be to keep the recycle sCO_2 stream flow rate constant and allow the TIT to vary**
- **Sensitivity case run on an incomplete combustion case with the recycle flow rate kept the same as for the complete combustion case**
  - Bypass fraction 1, maximum combustor flame temperature
- **Results found to be very close to the results for the constant TIT case**
  - 12 °C lower TIT
  - 4 MW greater gross turbine output
  - 1.6 MW greater cycle output
  - 0.12 percentage point higher cycle efficiency
  - Near equal increases for process output and efficiency



Constant Recycle Flow Case

Process & Cycle Efficiency versus CO Mole Fraction

- Plot shows process (blue) and cycle (red) efficiency as a function of CO mole fraction
- Solid lines correspond to constant TIT
- Dashed lines correspond to constant recycle flow rate
- Little difference in efficiency dependence on CO mole fraction for constant TIT versus constant recycle flow rate
- Results suggest that maintaining a constant TIT in the event of incomplete combustion is not critical
  - Provided variation in TIT and recycle flow rate is not too great



Comparison with Other Studies

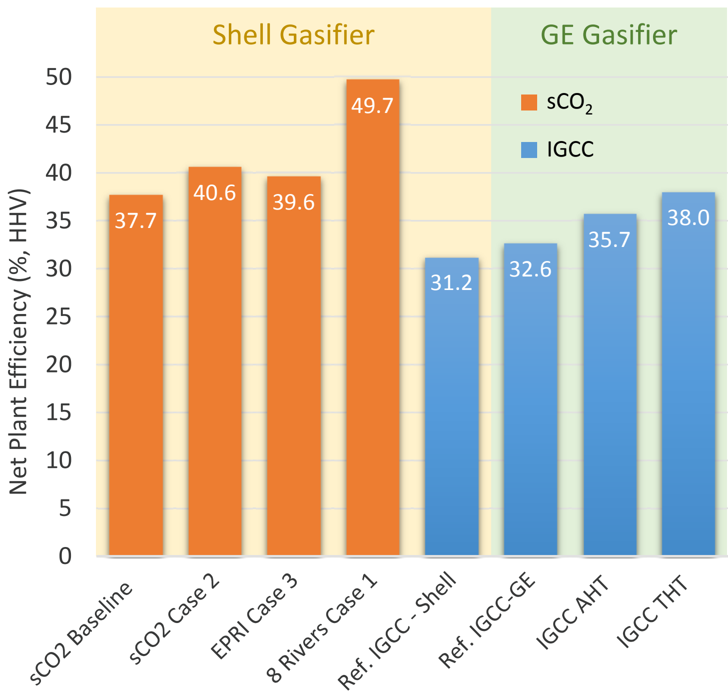
Plant Design and Performance Comparison

Item	sCO_2 Baseline	sCO_2 Case 2	EPRI Case 3 [3]	8 Rivers Case 1	Reference IGCC - Shell Gasifier [7]	Reference IGCC - GE Gasifier [7]	IGCC-AHT (Adv. H2 Turbine)	IGCC-THT (Transf. H2 Turbine)
Coal Type	Illinois #6	Illinois #6	PRB	Illinois #6	Illinois #6	Illinois #6	Illinois #6	Illinois #6
Coal Feed	Dry	Dry	Dry	Dry	Dry	Water Slurry	Water Slurry	Water Slurry
Gasifier Type	Shell	Shell	Shell	Shell	Shell	GE-RGC	GE-RGC	GE-RGC
Syngas Heat Recovery	Syngas cooler	Syngas cooler	Syngas cooler	Syngas cooler	Syngas cooler	Radiant Syngas cooler	Radiant Syngas cooler	Radiant Syngas cooler
Other Processes	Steam plant	Steam plant	Steam power cycle	None	Gas turbine steam cycle	Gas turbine steam cycle	AHT gas turbine steam cycle	THT gas turbine steam cycle
Sulfur Removal	AGR	AGR	AGR	DeSNOx	AGR	AGR	AGR	AGR
Turbine Cooling	Yes	Yes	No	?	Yes	Yes	Yes	Yes
Turbine Inlet Temperature (°C)	1204	1204	1123	1150	1337	1337	1450	1700
Net Plant Power (MWe)	562	606	583	~280	497	543	771	1057
Net Plant Efficiency (HHV, %)	37.7	40.6	39.6	49.7	31.2	32.6	35.7	38.0
Carbon Captured (%)	97.6	99.4	99.2	~100	90.0	90.0	90.0	90.0
Captured CO_2 Purity (%)	99.8	99.8	98.1	?	99.4	99.5	99.5	99.5
Water Withdrawal (gpm/MW_{net})	9.0	8.8	---	---	11.4	10.7	---	---

Comparison with Other Studies

Plant Design and Performance Comparison

- Thermal integration in the Optimized sCO_2 (Case 2) improves thermal efficiency by 2.9 percentage points relative to our Baseline sCO_2 case
- Both cases compare favorably to the EPRI sCO_2 study, which does not include turbine blade cooling or combustor pressure drops
- sCO_2 cases deliver higher efficiency than IGCC cases with a gas turbine + steam combined cycle power island
  - Change to GE gasifier may improve efficiency
  - Optimized sCO_2 outperforms advanced (AHT) and transformational hydrogen turbine (THT) cases from the IGCC Pathway Study
    - Turbine only comparison, with GE gasifier



Comparison with Other Studies

Economic Analysis Results – COE

- **The COE for the sCO_2 plant is 11-20 percent lower than the COE for the reference IGCC plant**
  - Both with and without T&S costs
- **Decrease in COE is primarily due to the higher efficiency of the sCO_2 plant**
- **Reduced COE in EPRI study primarily due to lower cost PRB coal**
- **IGCC AHT and THT cases based on a GE gasifier with a radiant syngas cooler**
  - TPC 15% lower than Shell gasifier
  - Net plant efficiency 1.4 percentage points higher
  - COE \$17.2/MWh lower (-11.3%)

Component COE ($/MWh)	sCO_2 Baseline	sCO_2 Case 2	EPRI Case 3 [3]	Reference IGCC - Shell	Reference IGCC - GE	IGCC AHT	IGCC THT
Capital	79.2	70.1	85.8	87.0	74.2	61.0	53.6
Fixed O&M	19.4	17.2	13.0	20.5	18.2	14.6	12.5
Variable O&M	11.2	10.0	13.0	13.0	12.2	10.2	9.1
Fuel	26.6	24.7	15.8	32.1	30.7	28.1	26.4
Total (w/o T&S)	136.4	122.0	127.6	152.6	135.4	114.0	101.6
CO2 T&S	8.8	8.3	8.3	9.8	9.2	8.4	7.9
Total (w / T&S)	145.2	130.3	135.9	162.4	144.7	122.4	109.5

Comparison with Other Studies

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