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

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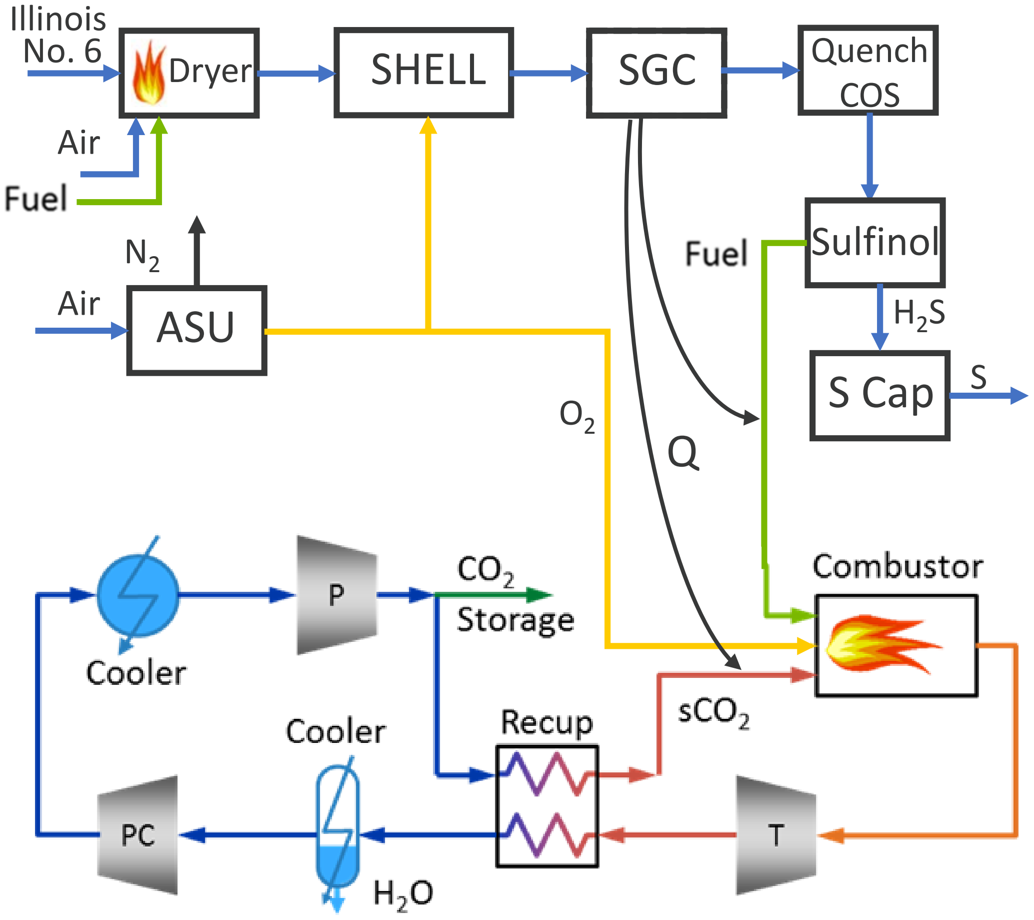
# Technology Overview – Direct $sCO_2$ Cycles

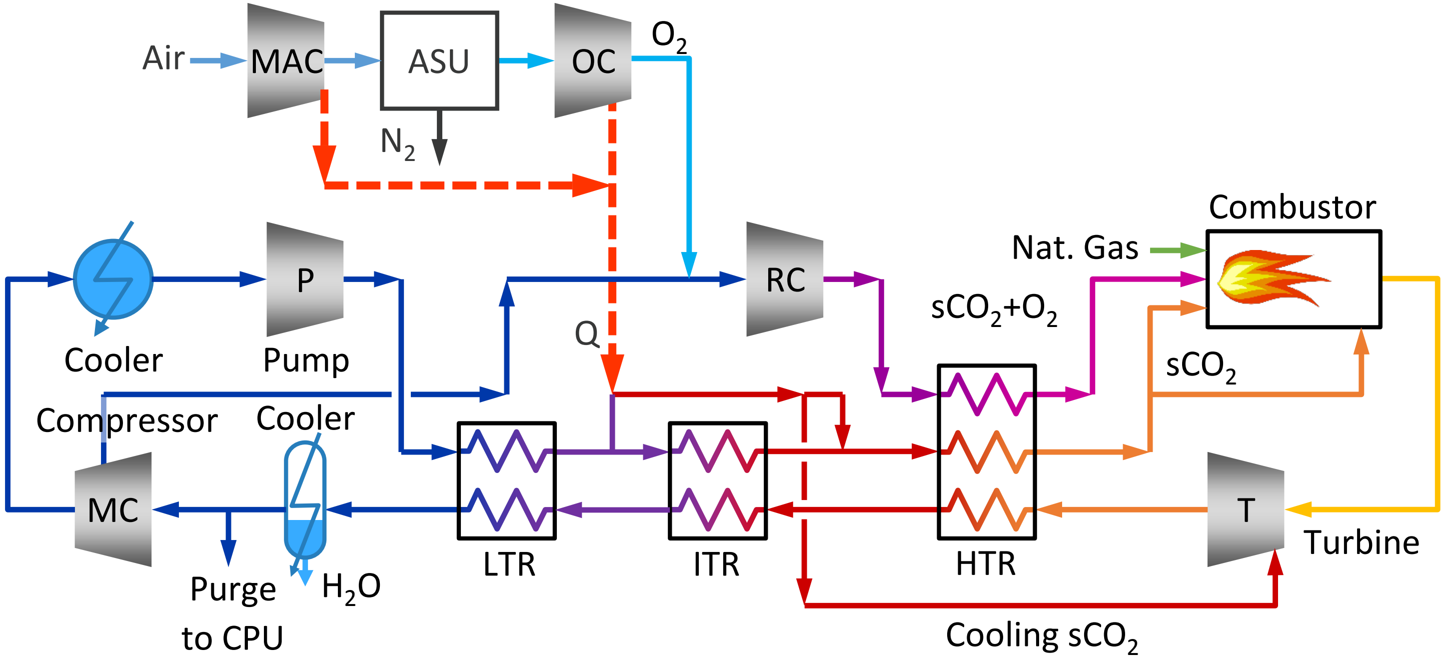
## Characteristics and Benefits

- **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

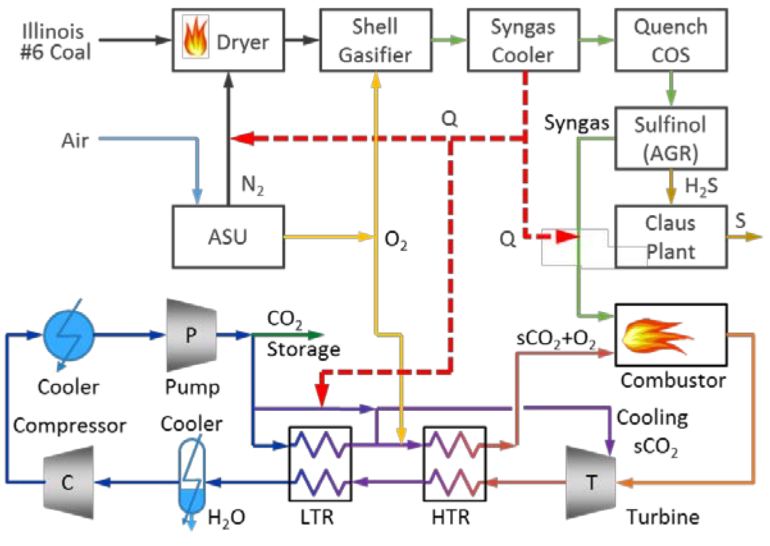
- <u>Objective</u>: Determine whether a natural gas-fired direct $sCO_2$ plant can compete economically against a natural gas combined cycle (NGCC) plant with carbon capture and storage (CCS)
- <u>Approach</u>: Develop a performance and cost baseline for a NG-fired direct $sCO_2$ cycle
- NG-direct $sCO_2$ 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



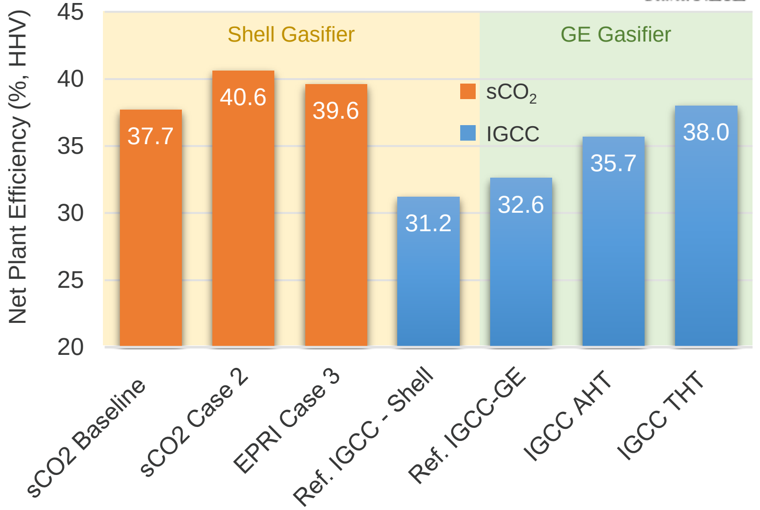
# Background

## 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%




*Source: NETL*

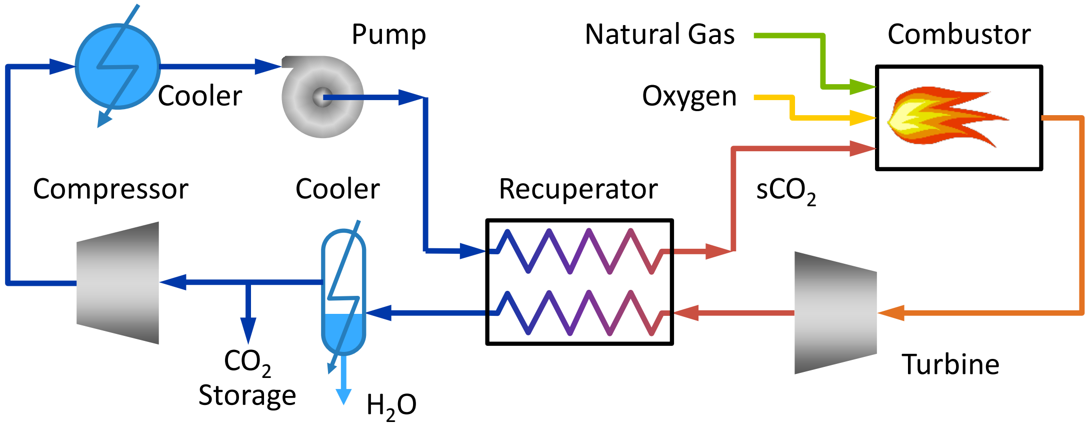



[1] Weiland, N.T., Shelton, W., Shultz. T., White, C.W., and Gray, D. "Performance and Cost Assessment of a Coal Gasification Power Plant Integrated with a Direct-Fired sCO2 Brayton Cycle," Report: NETL-PUB-21435, 2017.
[2] Weiland, N.T., and White, C.W., "Techno-economic Analysis of an Integrated Gasification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

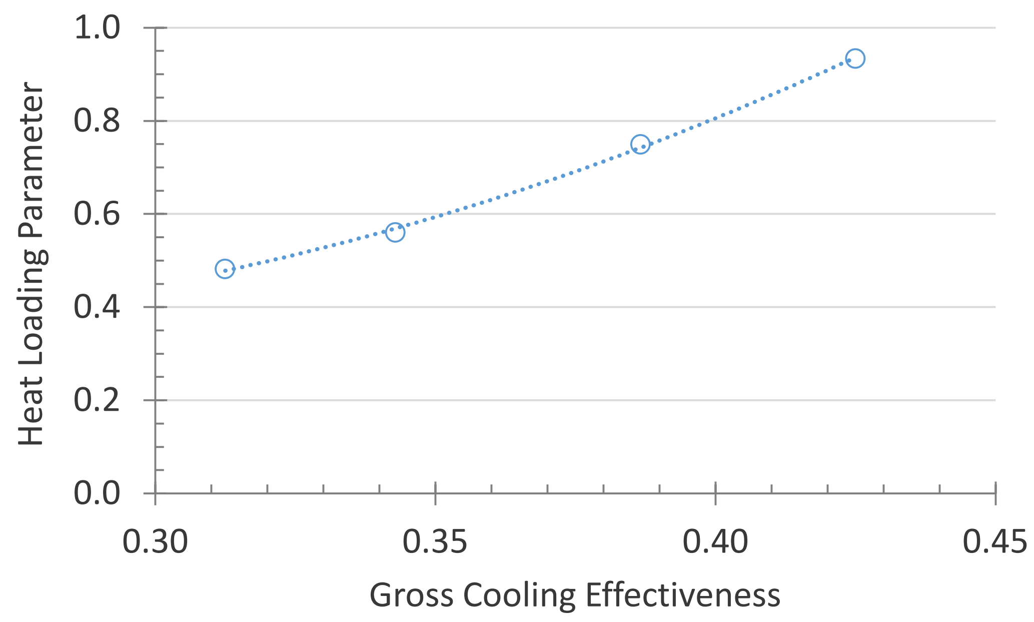



| Section | Parameter | Baseline $sCO_2$ Cycle |
|---|---|---|
| Combustor | $O_2$ purity | 99.5% |
| | Excess $O_2$ | 1% |
| | Pressure drop | 689 kPa (100 psid) |
| | Heat loss | Zero |
| Turbine | Inlet temp | 1204 °C (2200 °F) |
| | $P_{inlet}$ | 30.0 MPa |
| | PR, $P_{exit}$ | 10.2, 2.94 MPa |
| | 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 =** $(\dot{m}_{coolant}\, c_{p,coolant}) / (2\, H_{gas}\, A_{gas})$

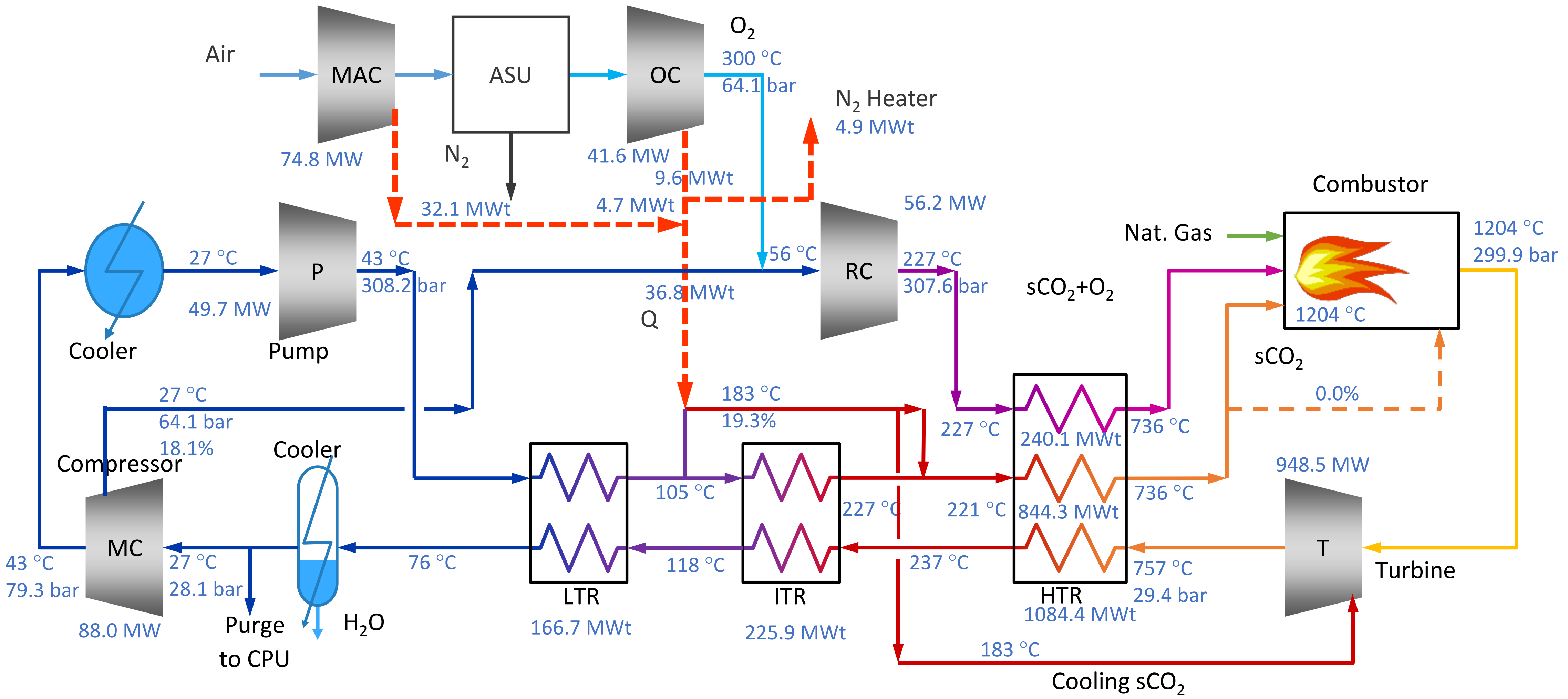
$H_{gas}$ = average external gas heat transfer coefficient

$A_{gas}$ = 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.

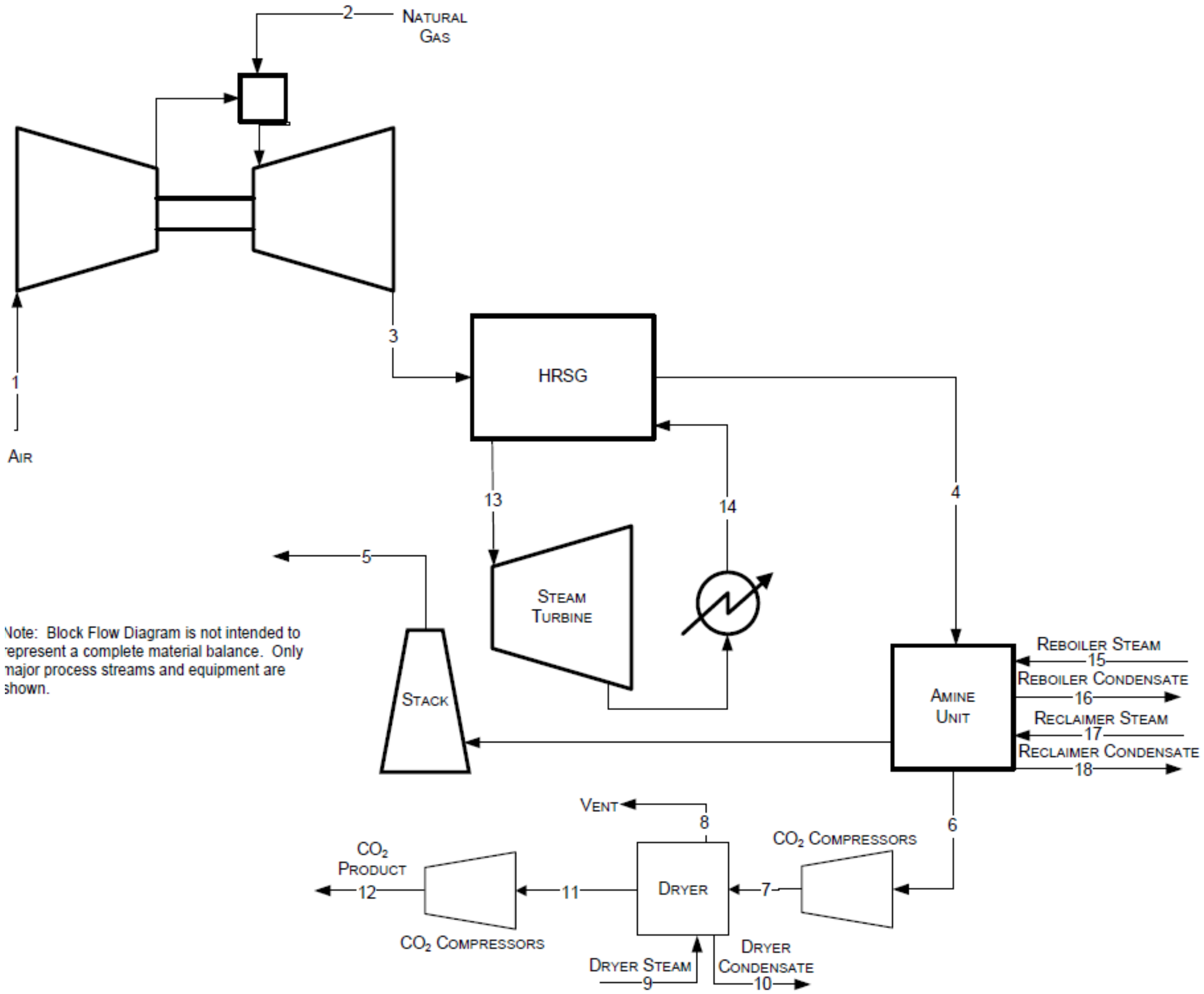
# Baseline Natural Gas Direct $sCO_2$ Plant

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**

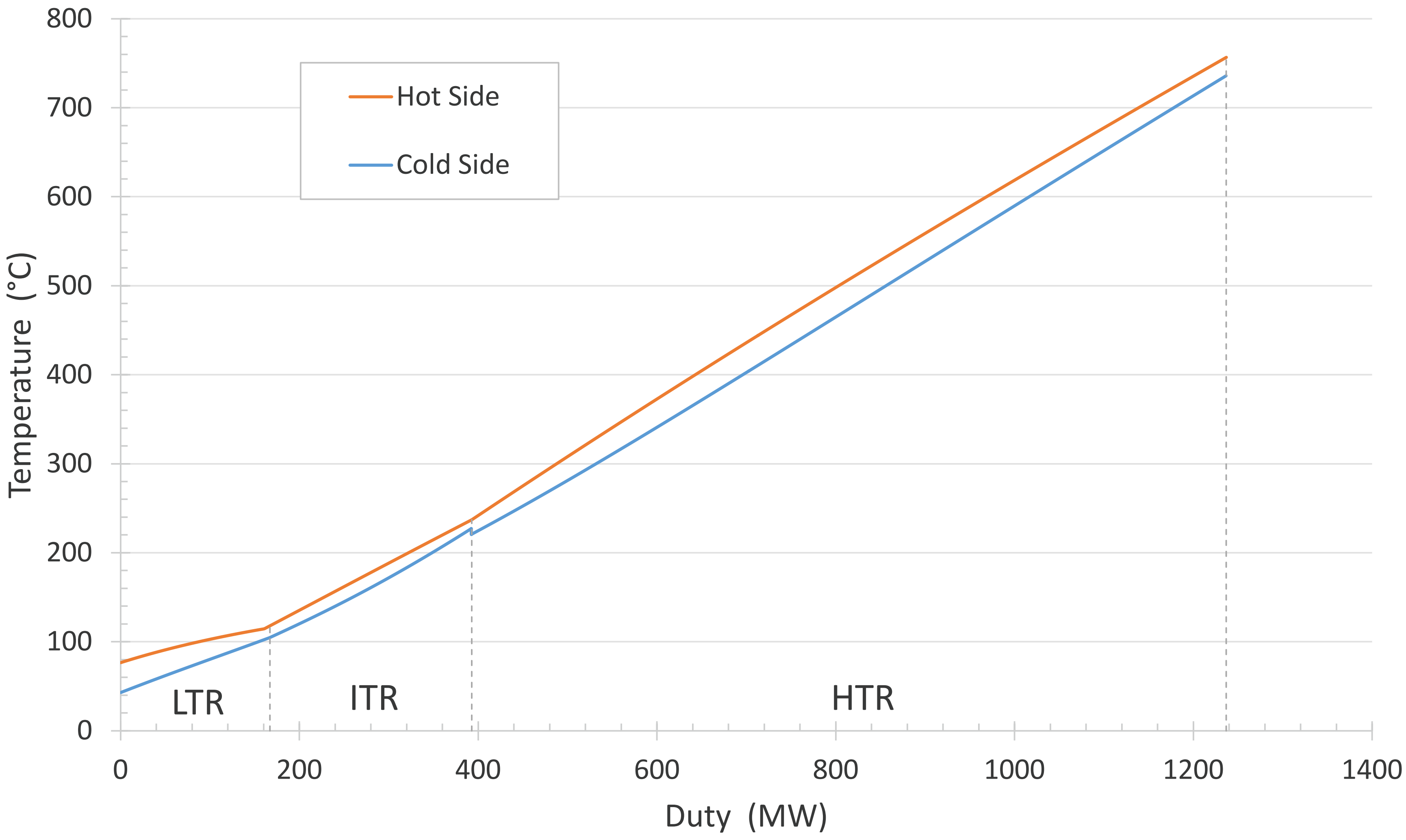
| Parameter | $sCO_2$ Cycle | NGCC Cases with $CO_2$ Capture[6] SOTA 7FA.05 | SOTA 7FA.05 +EGR | SOTA H-frame | Adv. J-frame |
|---|---|---|---|---|---|
| Turbine Inlet Temperature, °C | 1204 | 1359 | 1363 | 1487 | 1621 |
| Turbine Pressure Ratio | 10.2 | 17 | 17 | 20 | 23 |
| HHV Thermal Input, $MW_{th}$ | 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

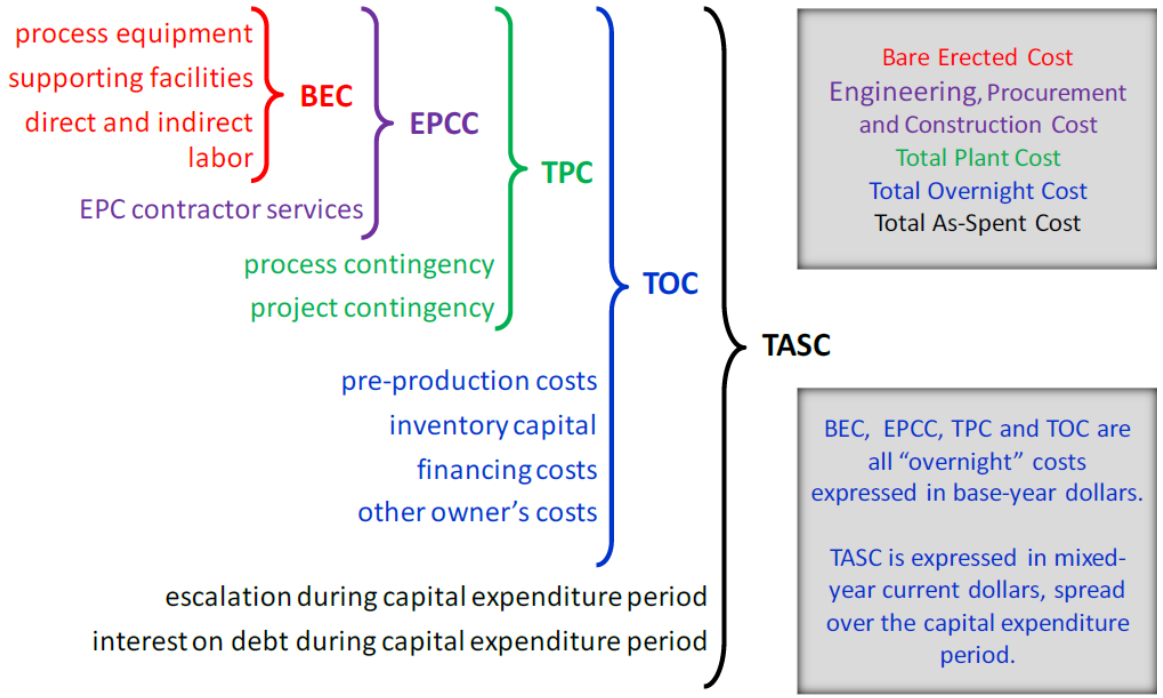
- Minimum $T_{approach}$ occurs at the hot end of the ITR
- Large $T_{approach}$ at the cold end of LTR due to water condensation on the hot side
- Average $T_{approach}$ just above 25 °C
- Average LMDT is a little below 18 °C



# Methodology – Economic Analysis

## 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)




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

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


[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

- **$sCO_2$ 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

- **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

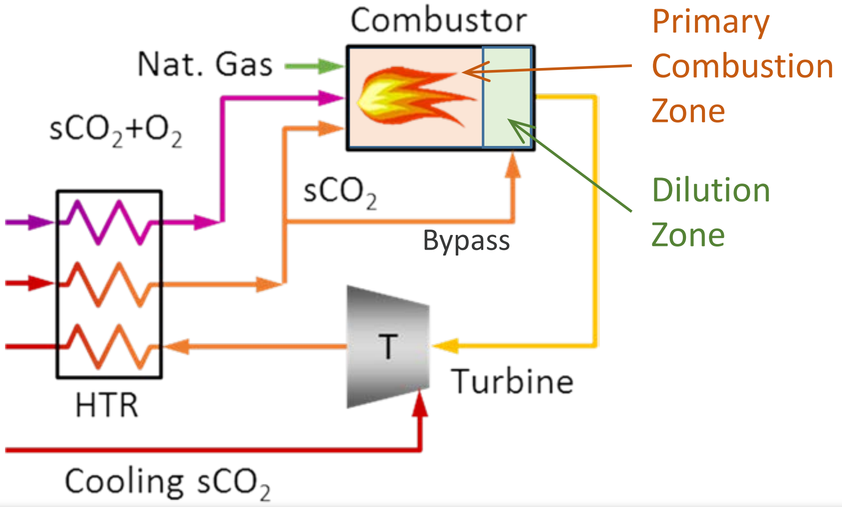
[8] R. Allam, M. Palmer, G. J. Brown, J. Fetvedt, D. Freed, H. Nomoto, M. Itoh, N. Okita and C. Jones Jr., "High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating Atmospheric Emissions, Including Carbon Dioxide," *Energy Procedia,* **37**:1135-1149, 2013.
[9] International 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 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



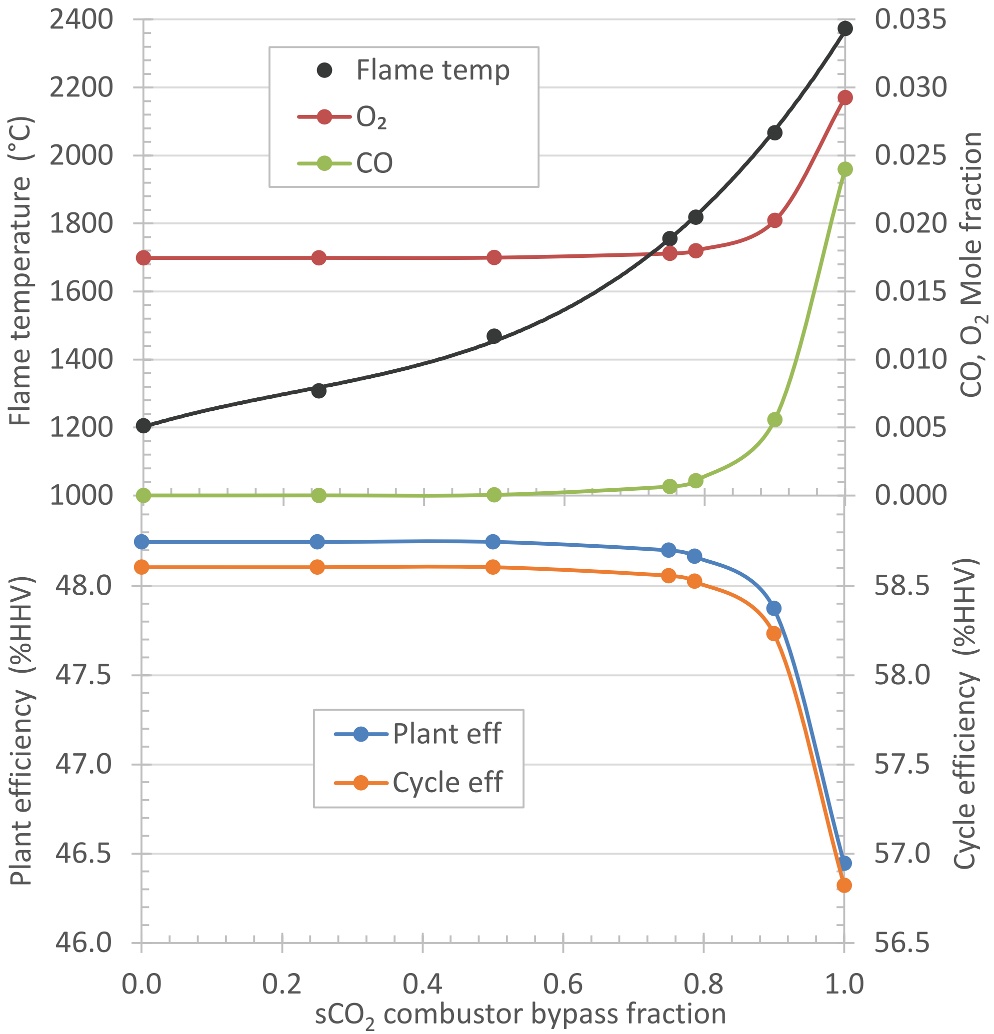

$$C_xH_y + (x/2 + y/4)\,O_2 \rightarrow x\,CO + y/2\,H_2O$$
$$CO + \tfrac{1}{2}\,O_2 \leftrightarrow CO_2$$

- **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**

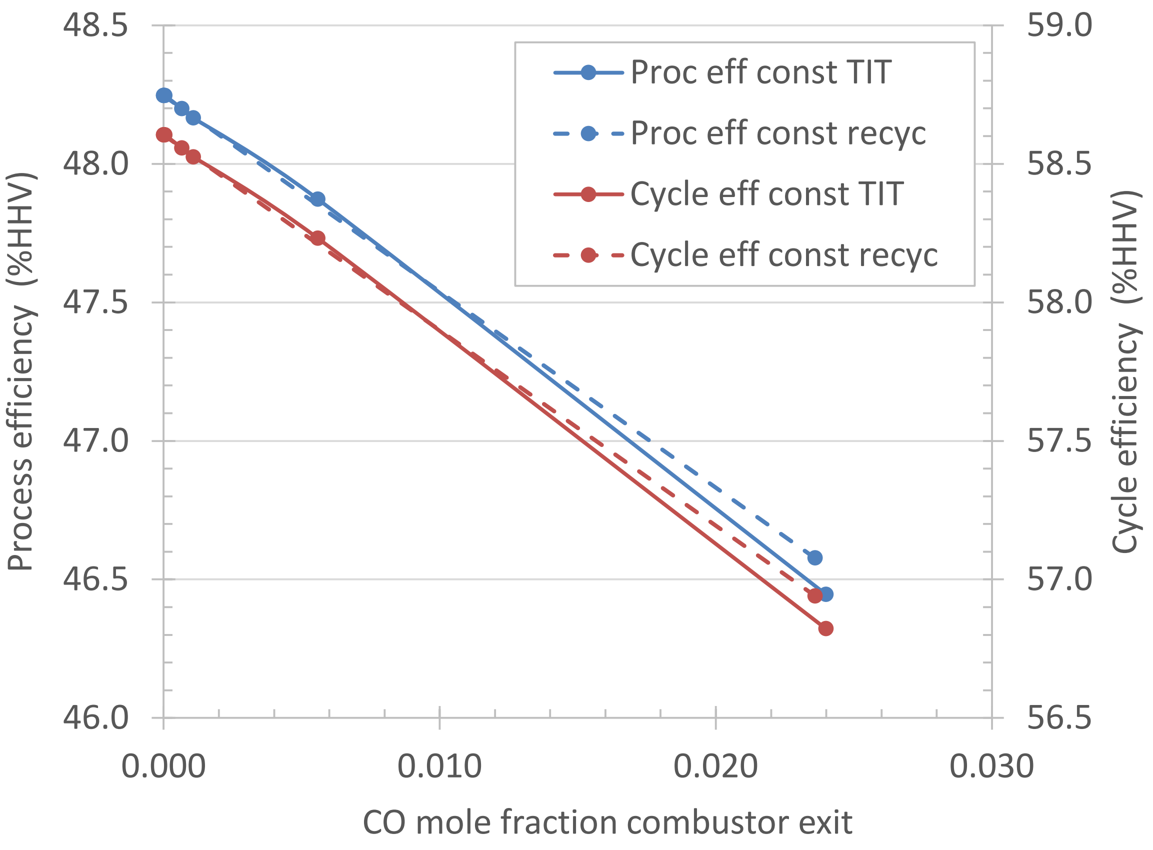


# Sensitivity to Incomplete Combustion

Process & Cycle Efficiency versus CO Mole Fraction



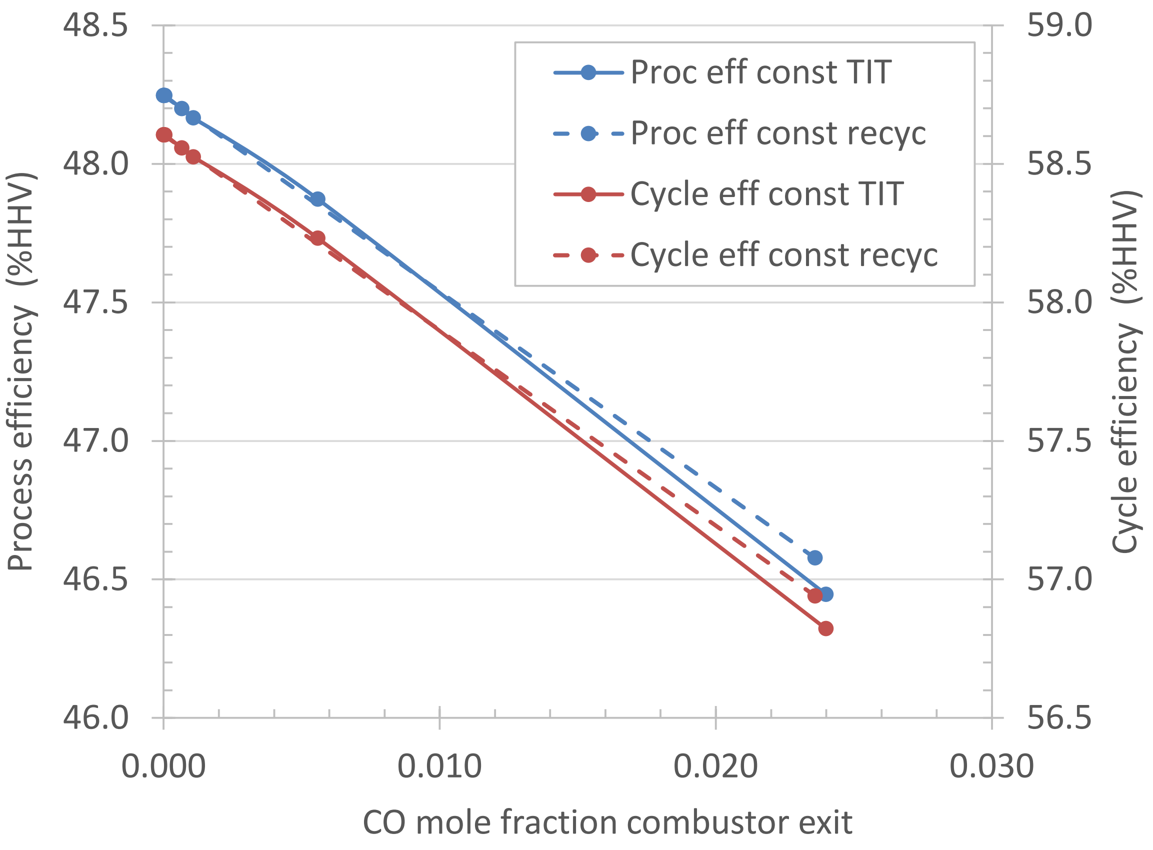
- **Plant and cycle efficiency have a roughly linear dependence on CO mole fraction**
  - Also accounts for effect of associated $O_2$ mole fraction from $CO_2$ dissociation
  - $sCO_2$ impurities decrease fluid density, increasing required compression power
- **Process and cycle efficiency drops by 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

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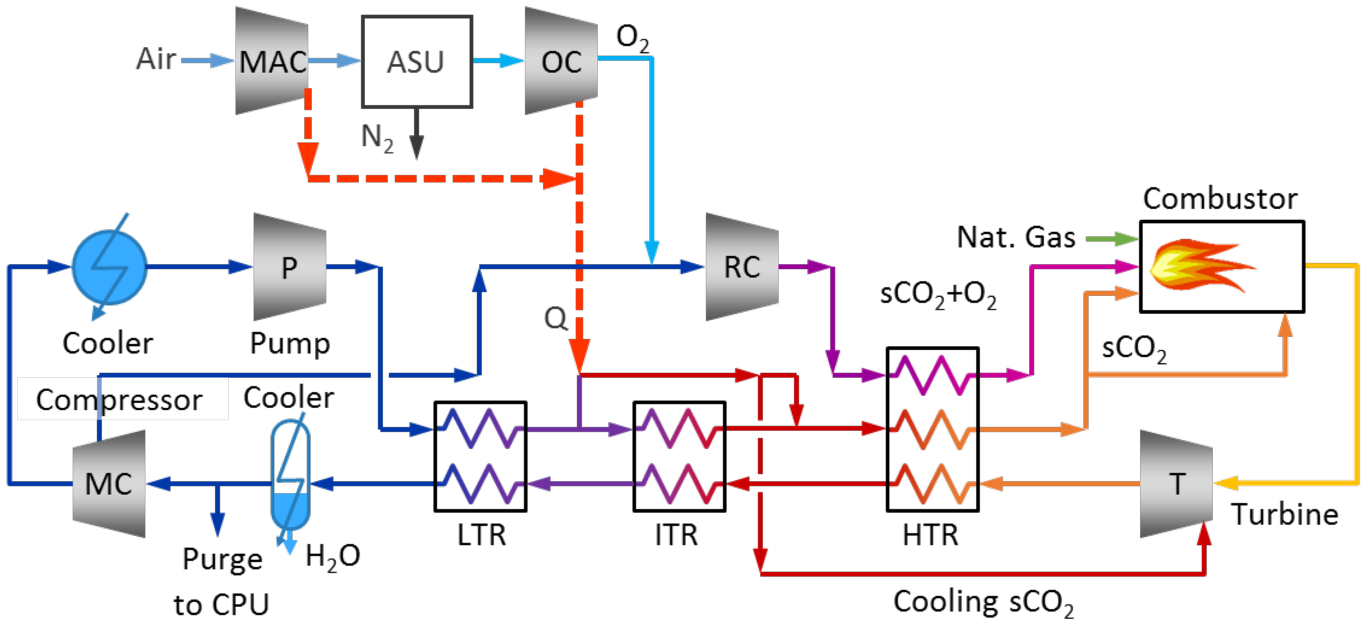
- The baseline $sCO_2$ plant design developed in this work will undergo further optimization and modification in future studies to develop a more cost-effective plant design
- Potential for efficiency improvement exists in implementing a high pressure ASU model in which the oxygen is pumped to high pressure 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

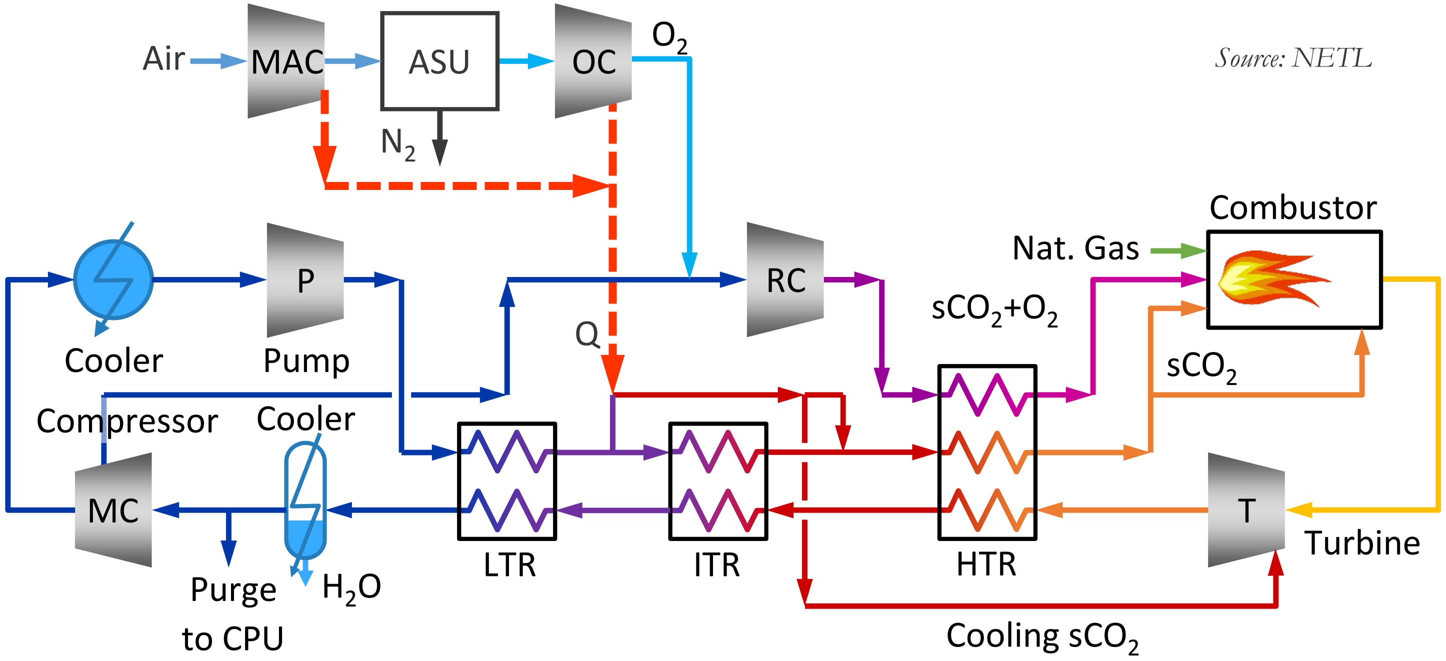
# Questions?

# 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

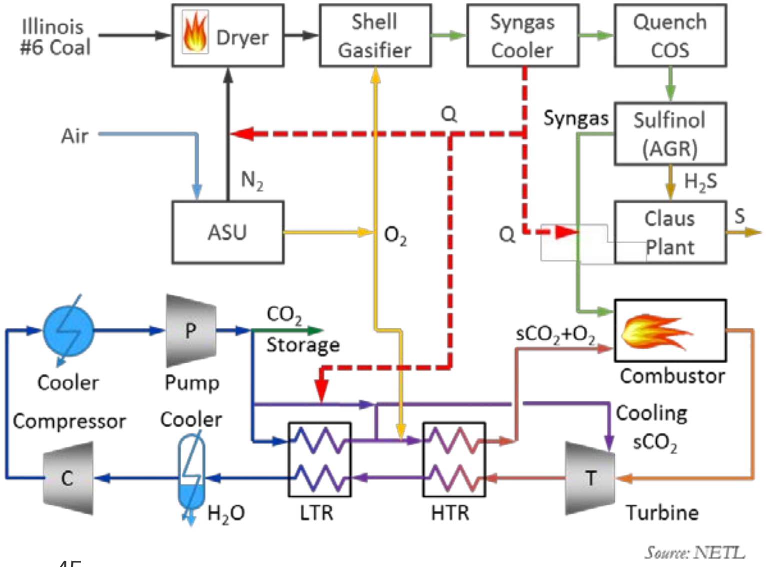
- $sCO_2$ plant HHV efficiency currently 48.2% *with* 99% carbon capture, with 3% lower COE than baseline NGCC plant with CCS ($\eta_{HHV}$ = 45.7%)
- Changing $O_2$ compressor to a LOX pump may improve plant efficiency by ~3 percentage points

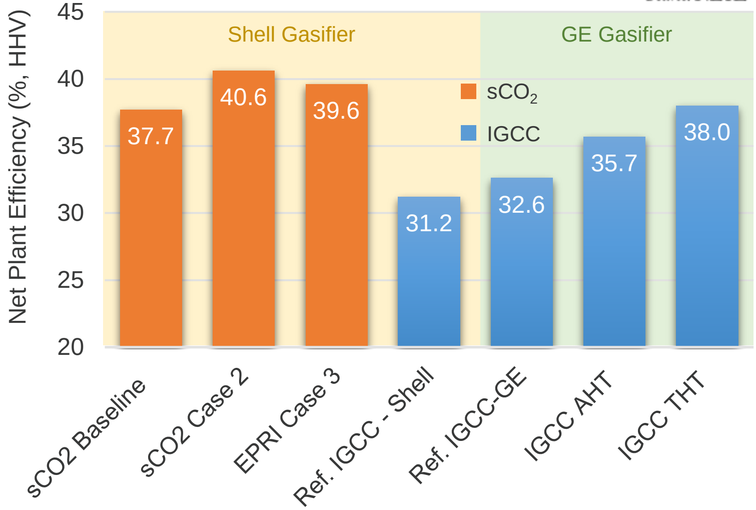


# Integrated Gasification Direct $sCO_2$ Cycle Study

## Summary

- **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.

# Integrated Gasification Direct $sCO_2$ Cycle Study

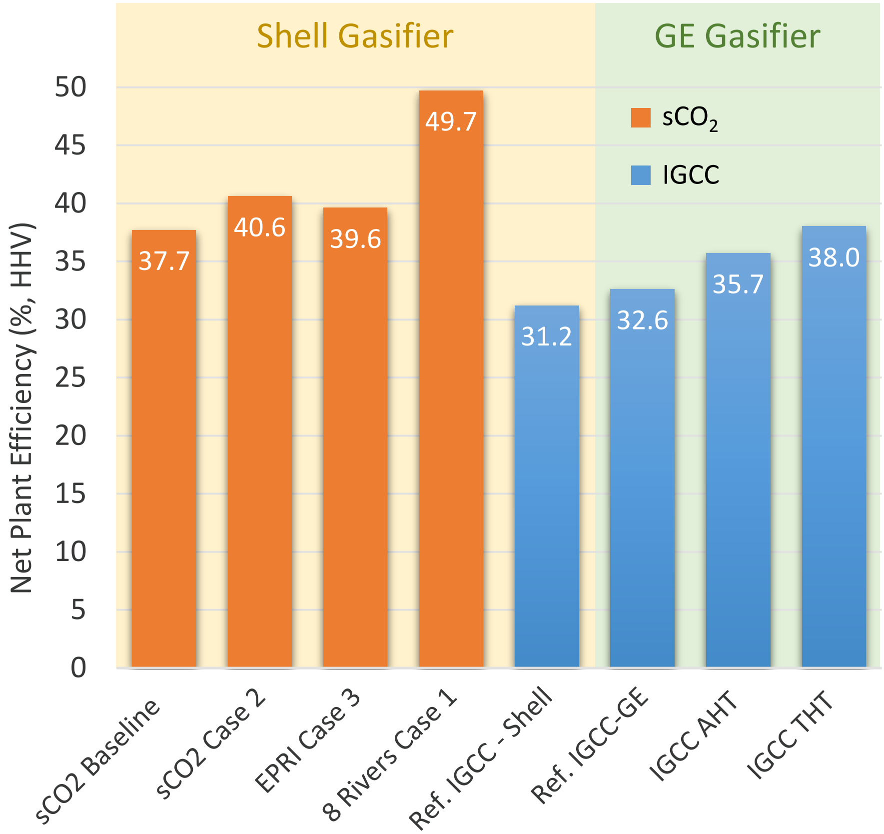
## Plant Design and Performance Comparison

| 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 | --- | --- |

# Integrated Gasification Direct $sCO_2$ Cycle Study

## 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



# Integrated Gasification Direct $sCO_2$ Cycle Study

## Economic Analysis Results Comparison – 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
  - COE \$17.2/MWh lower (-11.3%)