# Overview of DOE Energy Systems - Fossil Energy Power Systems

NATIONAL ENERGY TECHNOLOGY LABORATORY

*Presented at the Technical Review Meeting - Evaluation of Welding Issues in High Nickel and Stainless Steel Alloys for Advanced Energy Systems*

*March 10, 2021*

Solutions for Today | Options for Tomorrow

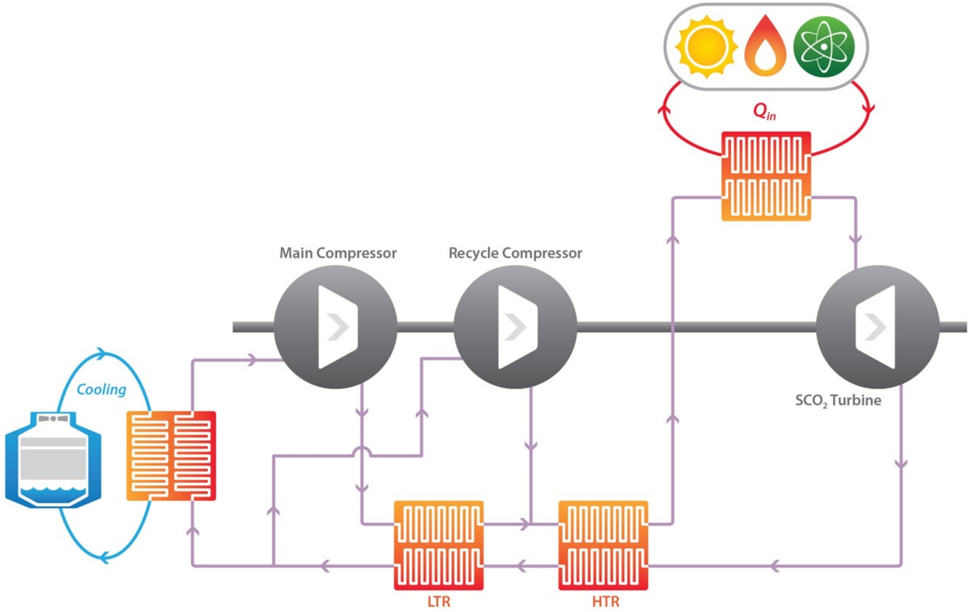
*Presented by: Rich Dennis for Nate Weiland*

U.S. DEPARTMENT OF ENERGY

# Presentation Overview

*Overview of DOE Energy Systems - Fossil Energy Power Systems*

- Supercritical carbon dioxide-based power cycles of interest to FE
- Application of the recompression Brayton cycle to boilers
- Advanced Ultra supercritical steam-based cycle
- Allam cycle
- Advanced Ultra-supercritical Component (ComTest) Project Update
- STEP heater
- Summary





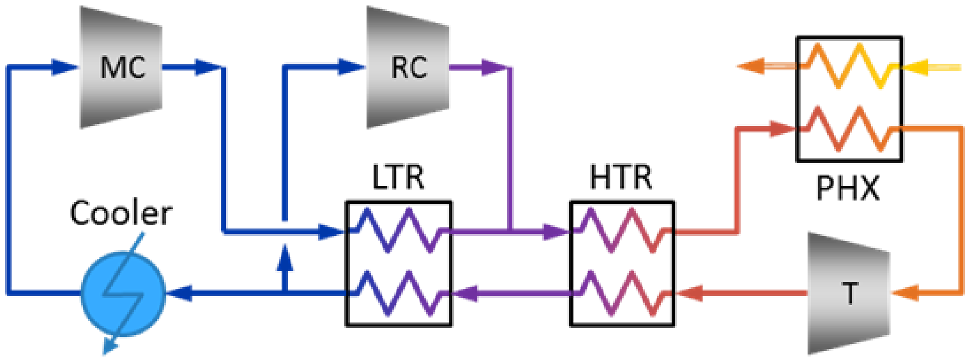

Welding photograph from *Advanced Ultra-supercritical Component (ComTest) Project Update*, EPRI, DOE Contract DE-FE0025064

# $sCO_2$ Power Cycles

## Two Related Cycles with Multiple Applications

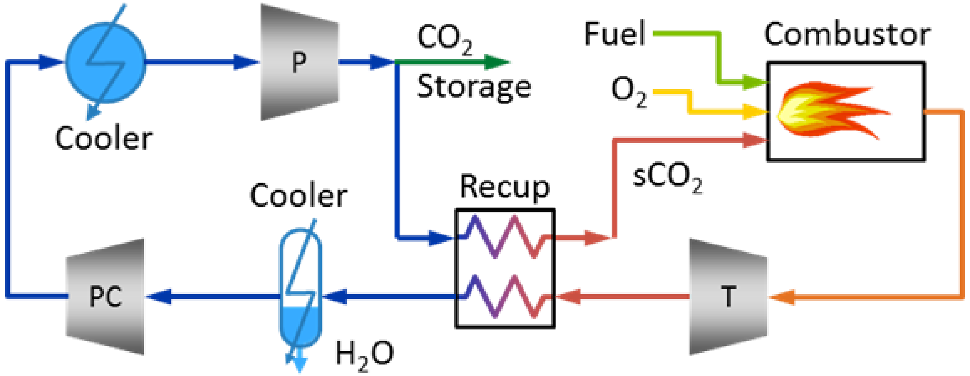
### Recompression Brayton Cycle

- Multiple applications: FE, CSP, NE, WHR
- Incumbent to beat: USC/AUSC boilers
- >50% cycle efficiency possible
- Extremely compact turbomachinery
- Adaptable for dry cooling

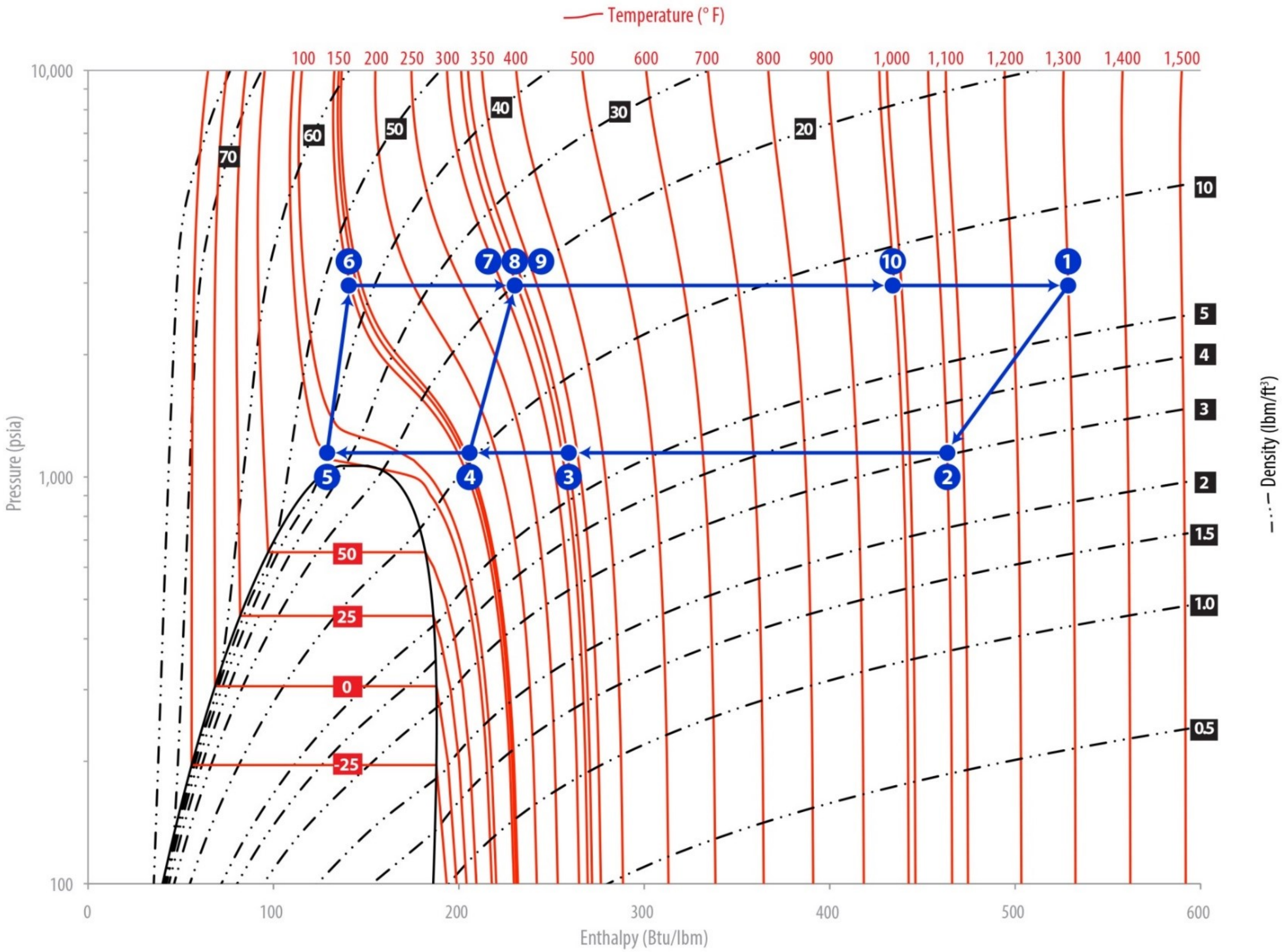



### Allam Cycle

- Fuel flexible: coal syngas and natural gas
- Incumbent to beat: NGCC w/ post CCS
- Compatible w/ RD&D from indirect cycle
- >95+ % $CO_2$ capture at storage pressure
- Net water producer, if dry-cooled



# $CO_2$ Pressure - Enthalpy Diagram for RCBC




| State Points (SP) | Function / equipment |
|---|---|
| 10 - 1 | Heat addition / boiler |
| 1 - 2 | Turbine expansion - work out |
| 2 - 3 | High temp. recuperation w/sp 9-10 |
| 3 - 4 | Low temp. recuperation w/ sp 6 – 7 |
| 4 - 5 | Cooling / heat rejection |
| 5 -6 | Main compression |
| 4 - 8 | Re compression |

# Optimized Performance and Cost for Indirect sCO2 Coal Plants

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## Justification

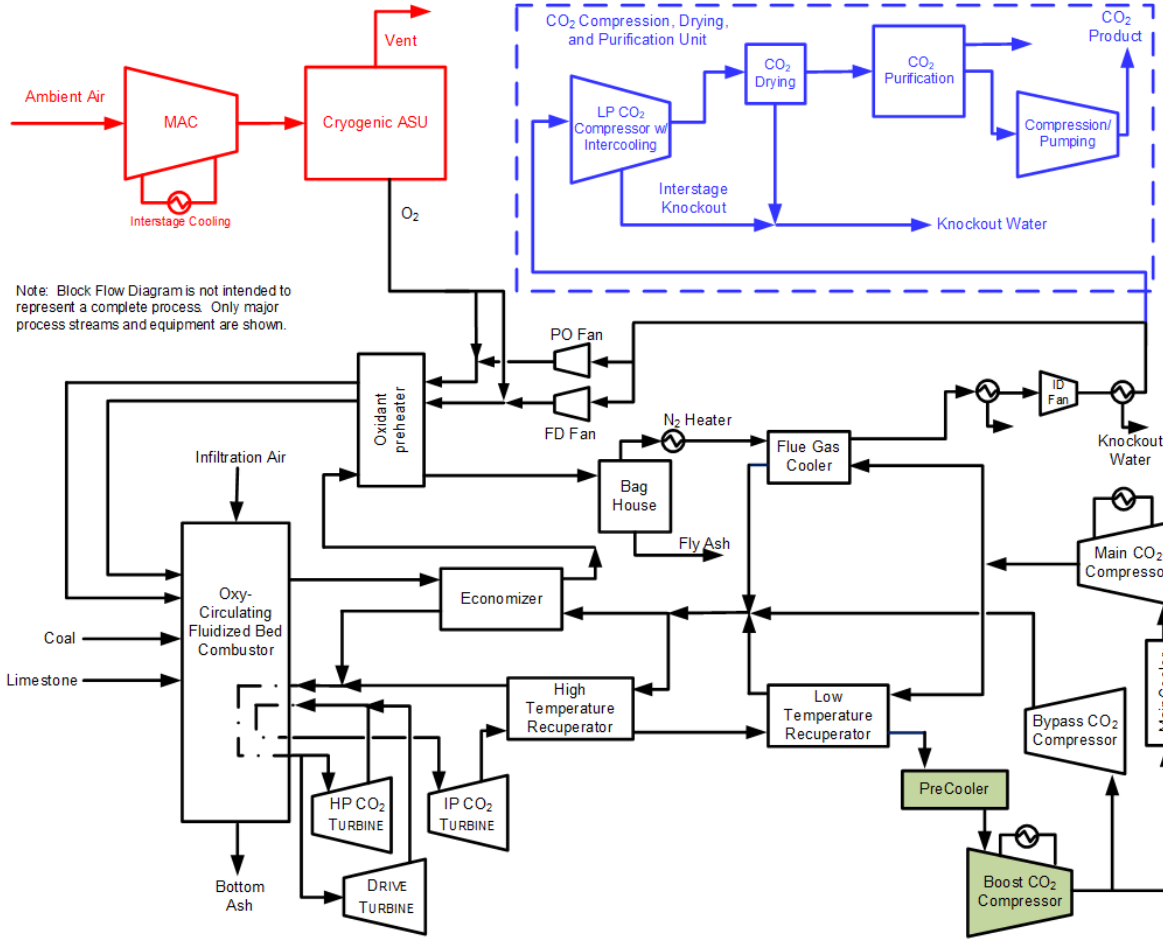
- Indirect-fired supercritical $CO_2$ power cycles are being explored as an attractive alternative to steam Rankine cycles for a variety of heat sources including fossil, CSP, Nuclear, waste heat etc.
- Understanding the performance and cost potential is important for future investment into the technology

## Highlights

- Coal-fired CFB heat source coupled to $sCO_2$ power cycles can be economically attractive compared to PC-fired Rankine plants
- Recompression cycle with reheat offered highest plant efficiency and lowest COE for both capture and non-capture plants
- Partial cooling cycles had higher COEs for Midwest ISO ambient conditions but are expected to outperform recompression cycles at higher ambient temperatures

## Outcomes

- Study is first of the kind to optimize $sCO_2$ plant designs using simultaneous optimization tools available under FOQUS platform while considering several design variables and sub-system models
- Identified CFB and plant designs that have potential to achieve lower cost of electricity



# Summary of Overall Plant HHV Efficiencies

Oxy-CFB with steam Rankin cycle VS $sCO_2$ modified recompression Brayton Cycles

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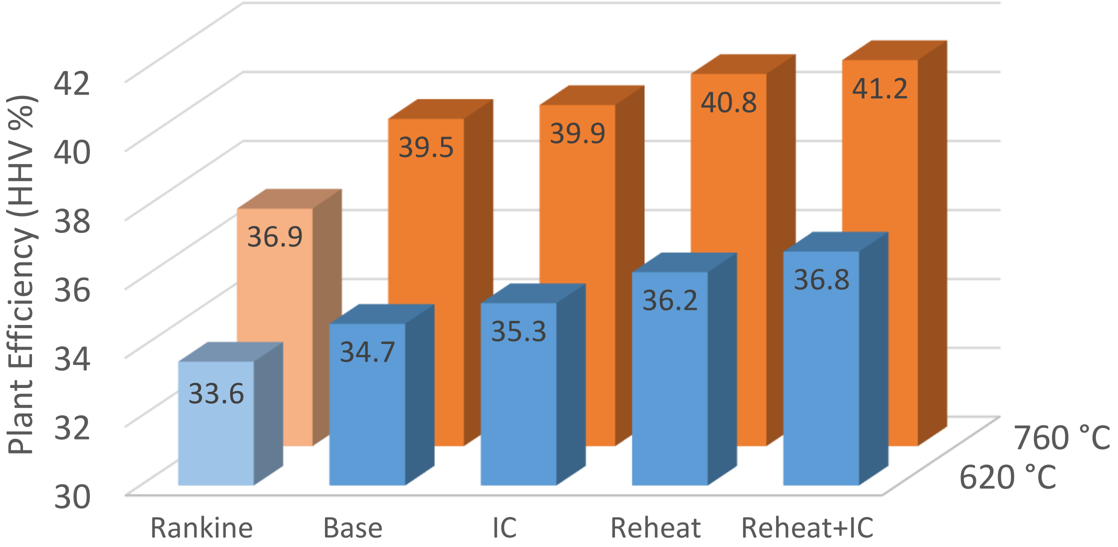
- **Relative to the steam Rankine cycles:**
  - At 620 °C, $sCO_2$ cycles are 1.1 – 3.2 percentage points higher in efficiency
  - At 760 °C, $sCO_2$ cycles are 2.6 – 4.3 percentage points higher
- **The addition of reheat improves $sCO_2$ cycle efficiency by 1.3 – 1.5 percentage points**
- **The addition of main compressor intercooling improves efficiency by 0.4 – 0.6 percentage points**
  - Main compressor intercooling reduces compressor power requirements for *both* the main and bypass compressors

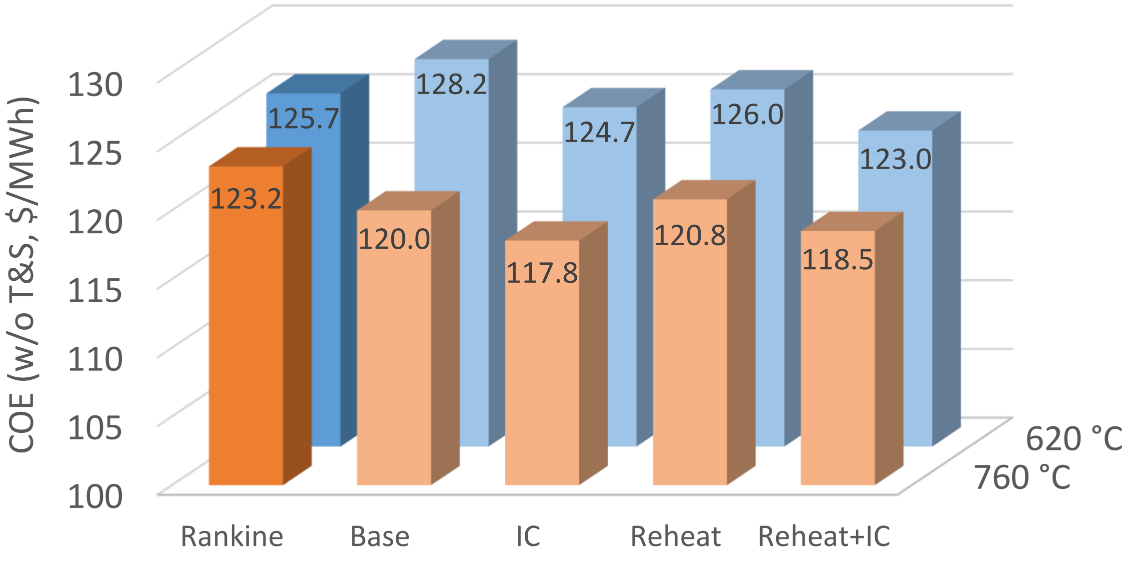



| Power Summary (MW) | B22F | Base | IC | Reheat | Reheat+IC |
|---|---|---|---|---|---|
| Coal Thermal Input | 1,635 | 1,586 | 1,557 | 1,519 | 1,494 |
| Turbine Power | 721 | 1,006 | 933 | 980 | 913 |
| $CO_2$ Main Compressor | | 160 | 154 | 148 | 142 |
| $CO_2$ Bypass Compressor | | 124 | 60 | 117 | 58 |
| Net Cycle Power | 721 | 711 | 708 | 704 | 702 |
| Air Separation Unit | 85 | 83 | 81 | 79 | 78 |
| Carbon Purification Unit | 60 | 56 | 55 | 54 | 53 |
| Total Auxiliaries, MWe | 171 | 161 | 158 | 154 | 152 |
| Net Power, MWe | 550 | 550 | 550 | 550 | 550 |

# Summary of COE (w/o $CO_2$ T&S)

Steam Rankine vs. $sCO_2$ Cases

- **Note that there is significant uncertainty in the CFB and $sCO_2$ component capital costs (-15% to +50%)**
  - Large capital cost uncertainties being addressed via external projects:
    - — $sCO_2$ turbine (GE-GR)
    - — Recuperators (Thar Energy)
    - — Primary heat exchanger (EPRI)
- **$sCO_2$ cases have comparable COE to steam Rankine plant at 620 °C, but reduced COE for 760 °C cases**




*Source: NETL*

- **Main compressor intercooling improves COE 2.2 – 3.5 $/MWh**
  - Low cost means of reducing $sCO_2$ cycle mass flow
- **Reheat reduces the COE for the 620 °C cases, but increases COE for turbine inlet temperatures of 760 °C**
  - Due to the high cost of materials for the reheat portions of the cycle in 760 °C cases

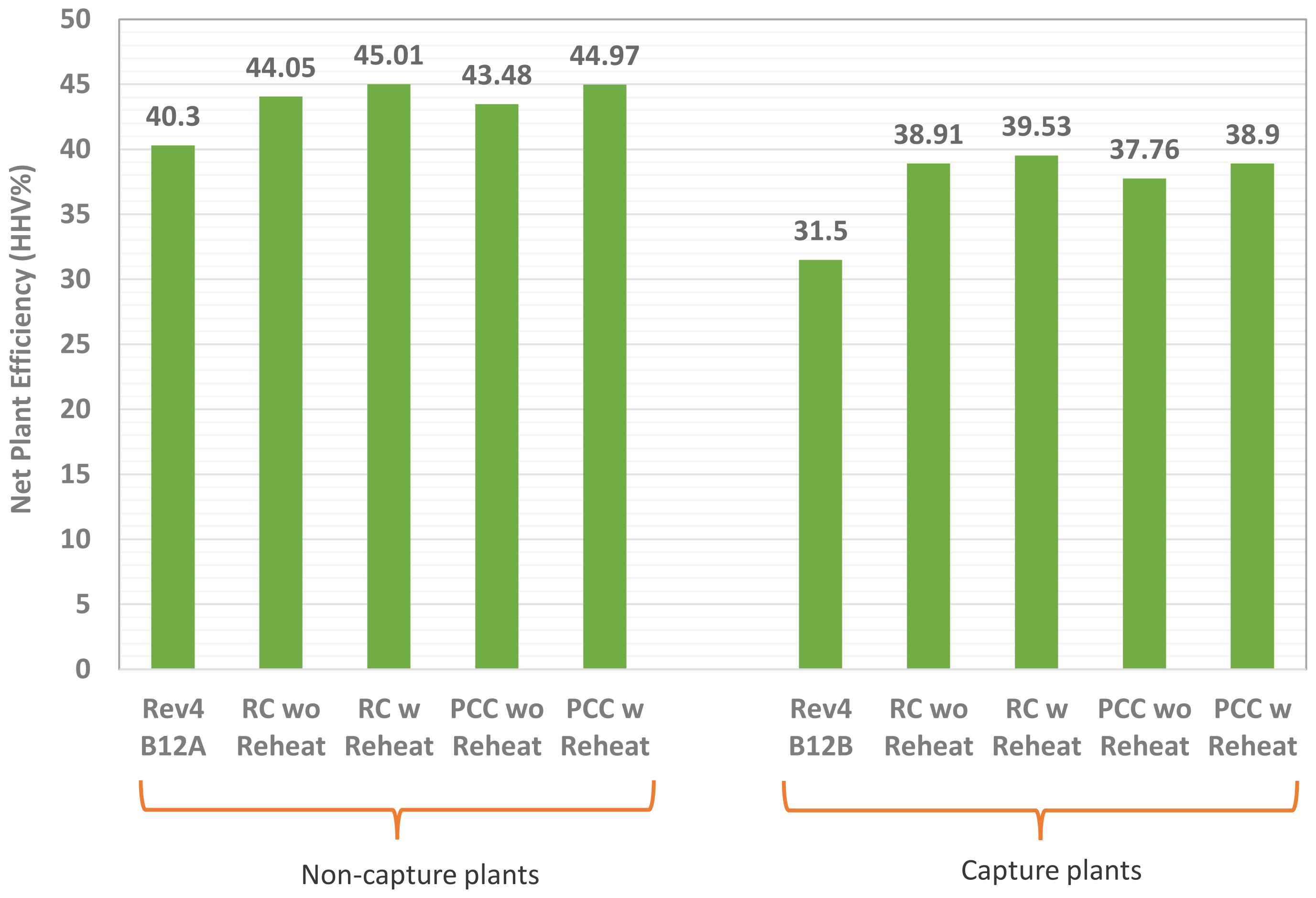
# Optimized Performance and Cost for Indirect sCO2 Coal Plants

## Approach

- Depending on the case, identified a list of 12 – 17 optimization variables
- Refined Aspen models and integrated with other component sub-models in FOQUS platform
- Used derivative-free optimization algorithms available under FOQUS platform to conduct automated optimization of plant designs to minimize COE

## Results

- For capture plants, recompression cycle with reheat offered 8% points higher plant efficiency and 14.6% lower LCOE compared to NETL Bituminous Baseline Rev4 B12B case
- For Non-capture plants, recompression cycle with reheat offered 4.7% points higher plant efficiency and 7% lower LCOE compared to NETL Bituminous Baseline Rev4 B12A case
- Optimal turbine inlet temperatures for $sCO_2$ power plants are in the range of 650 – 715 °C
- Lowering turbine inlet temperatures (to < 650 °C) and switching CFB tubing materials from Nickel to stainless steel alloys resulted in similar LCOE but lower plant efficiency



# Optimized Performance and Cost for Indirect sCO2 Coal Plants

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## Limitations

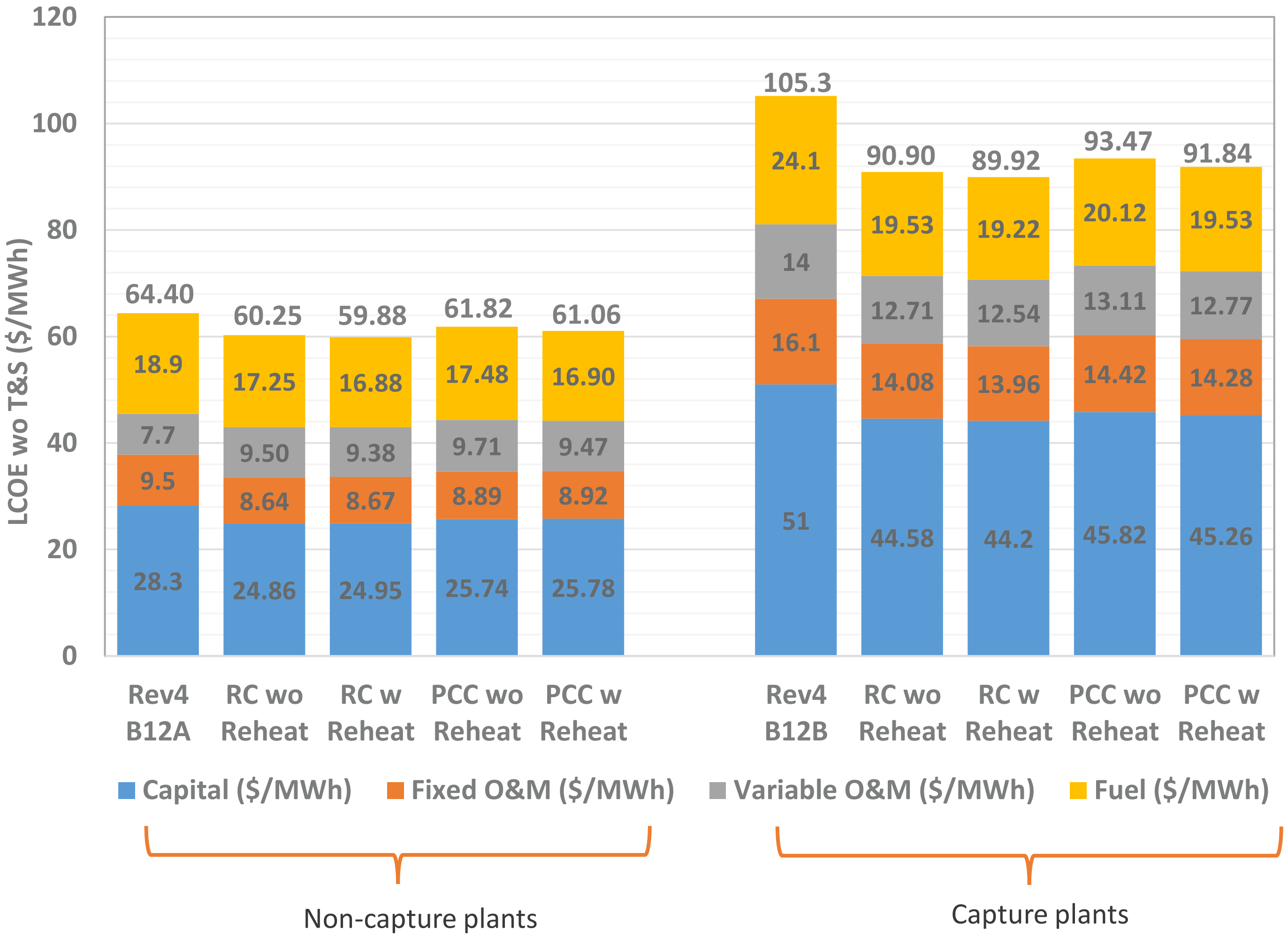
- Accuracy of CFB cost estimation is still potentially low due to lack of good cost estimates and use of low fidelity CFB model
- Low accuracy of power cycle turbo-machinery cost algorithms

## Suggested Follow-On Work

- Optimize $sCO_2$ plant designs for different plant sites and plant sizes using the developed FOQUS models
- Increase the CFB model fidelity by considering arrangement of tube banks, automated material selection and improving cost estimates for interconnecting piping
- Re-evaluate TEA/optimization as the technology evolves and more accurate cost sources become available
- Explore additional cases with relaxed design constraints for cycle split flows, cooler temperatures etc.

## Authors


- Sandeep Pidaparti, KeyLogic
- Chuck White, KeyLogic

# Updated Performance and Cost Evaluation for AUSC PC Plants

## Justification

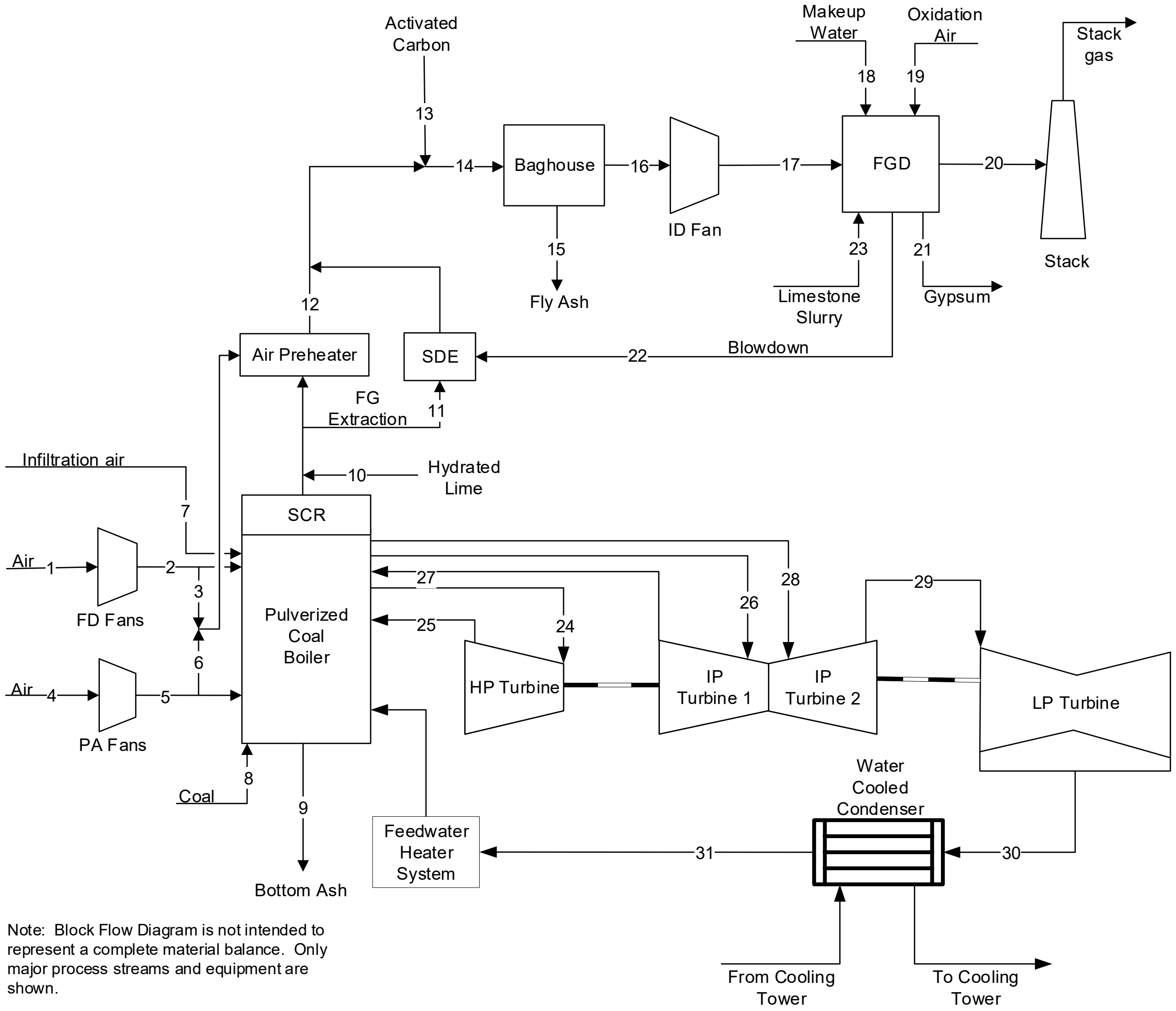
- Performance and cost implication of upgrading steam conditions and addition of second reheat is important for baseline comparisons
- Assessment could inform considerations made in meeting projected demands in future power markets

## Highlights

- All AUSC PC plants considered generate electricity at higher efficiencies and with lower carbon footprints than those operating at subcritical, supercritical (SC), and ultra-supercritical (USC) steam conditions
- Double-reheat cycle offered highest net plant efficiency (HHV) for both capture and non-capture plants
- Additional advanced materials required for the second reheat loop negated any fuel savings gained from improved efficiency

## Outcomes

- Levelized Cost of Electricity (LCOE) is lower for all single-reheat AUSC PC plants and for the capture double-reheat AUSC PC plant when compared to NETL Bituminous Baseline Rev4 SC PC cases
- Upgrading AUSC main steam pressure to 4,250 PSIG shows negligible gains over AUSC main steam pressure at 3,500 PSIG




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

# Updated Performance and Cost Evaluation for AUSC PC Plants

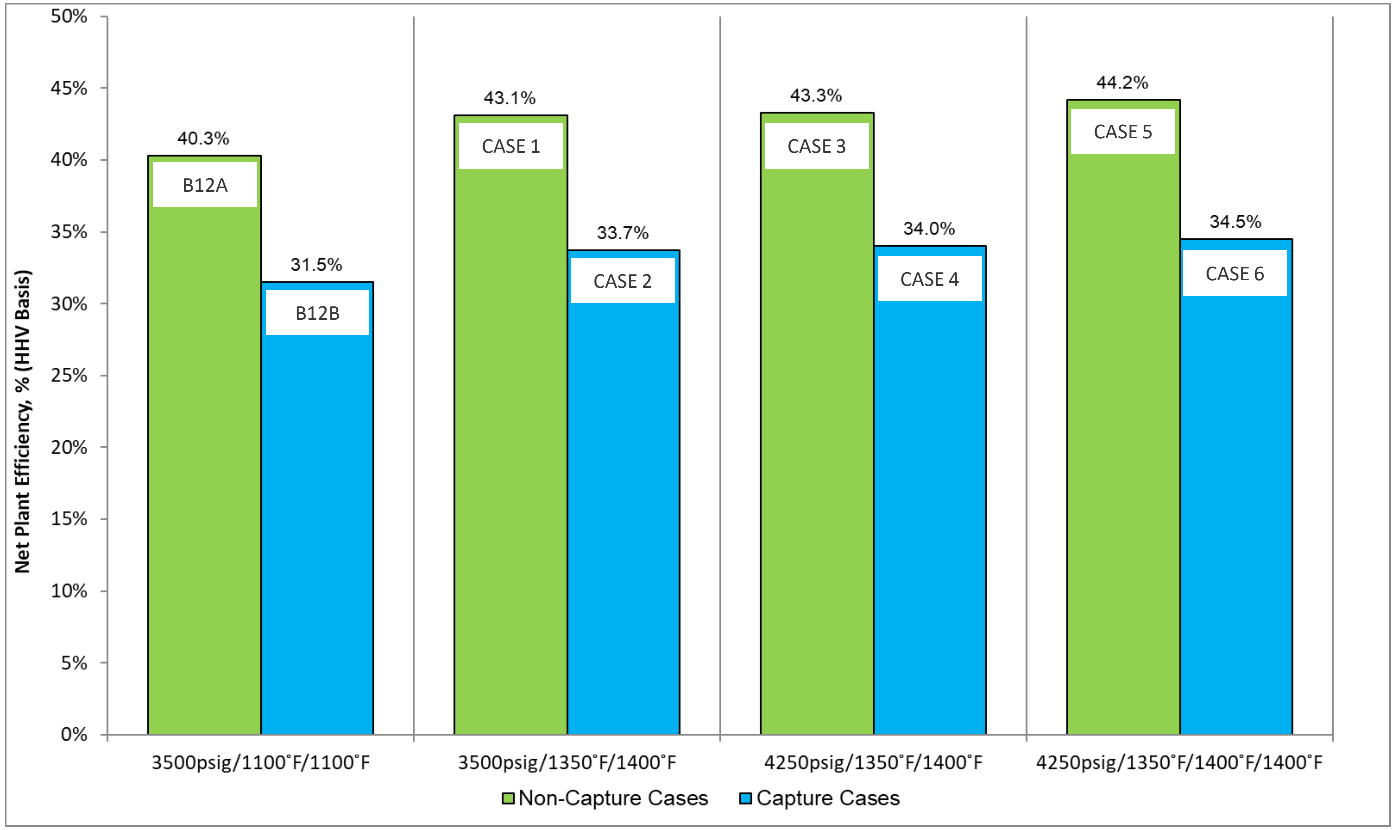
## Updated Performance and Cost Evaluation for AUSC PC Plants

### Approach

- Conduct literature review to collect updated information on AUSC boiler/turbine technologies, costs, and configurations, specifically those for double-reheat cases
- Update Aspen models to be consistent with model versions used in NETL Bituminous Baseline Rev4, altering modeling tools for incorporation of double-reheat cases as necessary
- Employ third-party resources for optimization and detailed cost and performance estimates of double-reheat cases
- Use performance data to create cost estimates and determine LCOE for each case, following NETL Quality Guidelines for Energy System Studies methodologies

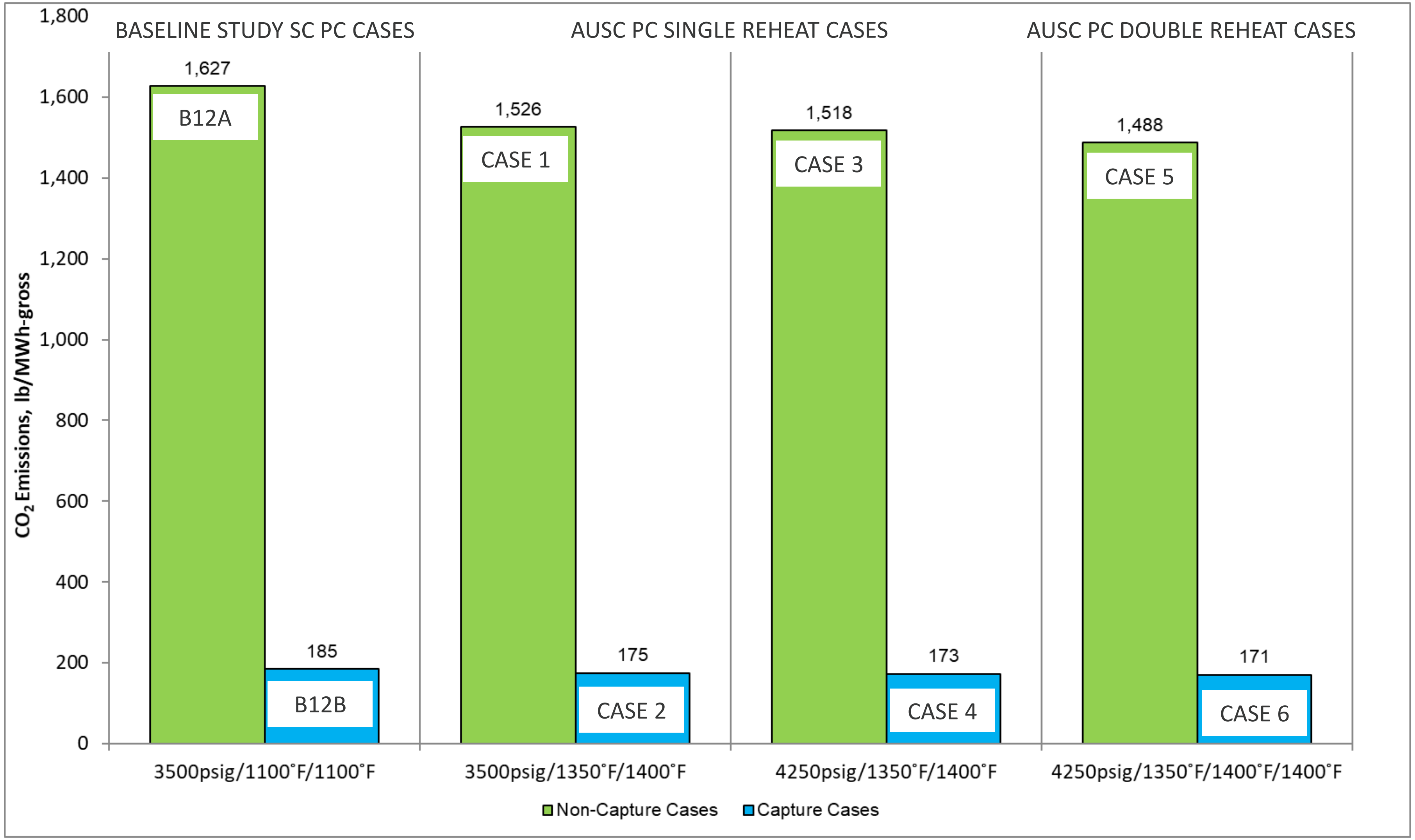
### Limitations

- Cost estimates of plant components containing advanced alloy materials rely on data based on limited manufacture and procurement quantities to date
- Cost estimates reflect technical maturity of a conceptual, inverted tower PC boiler



# Updated Performance and Cost Evaluation for AUSC PC Plants

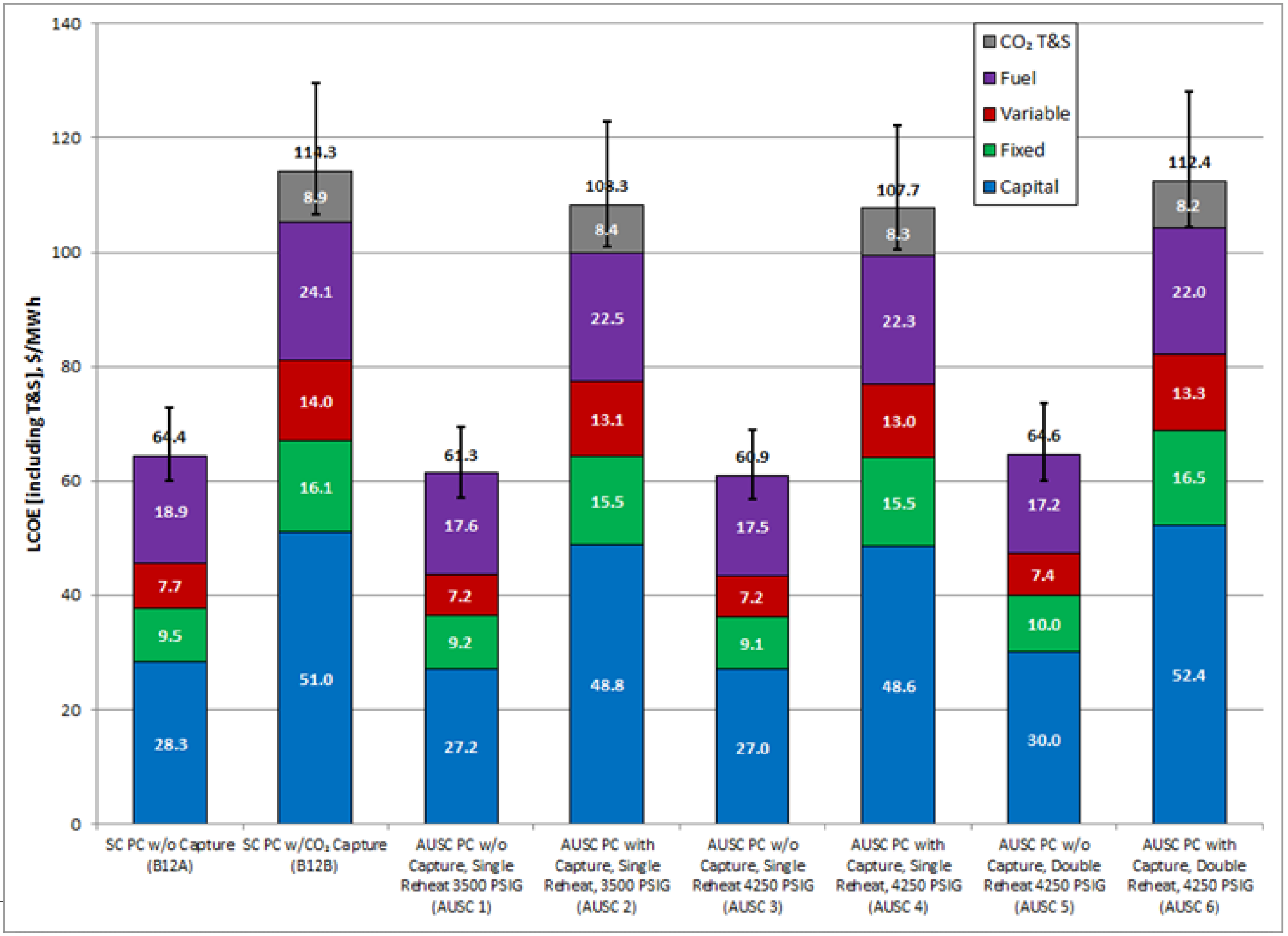
## $CO_2$ Emissions



# Updated Performance and Cost Evaluation for AUSC PC Plants

## Results

- For capture plants, upgrading to AUSC conditions offered 2.2-3.0 points higher net plant efficiency and 1.9-6.6 $/MWh lower LCOE compared to NETL Bituminous Baseline Rev4 B12B case
- For non-capture plants, upgrading to AUSC conditions offered 2.2-3.0 points higher plant efficiency and for single-reheat cases, 3.1-3.5 $/MWh lower LCOE compared to NETL Bituminous Baseline Rev4 B12A case
- Double-reheat non-capture plant shows increased LCOE compared to all other non-capture cases




## Conclusions

- AUSC PC power plants offer gains in efficiency over traditional subcritical, SC, and USC PC power plants
- Some fuel savings are offset by increased capital costs at AUSC conditions, affecting LCOE
- AUSC PC power plants show negligible efficiency gains and LCOE improvement with increased steam pressure
- Additional reheat loop is not economically beneficial

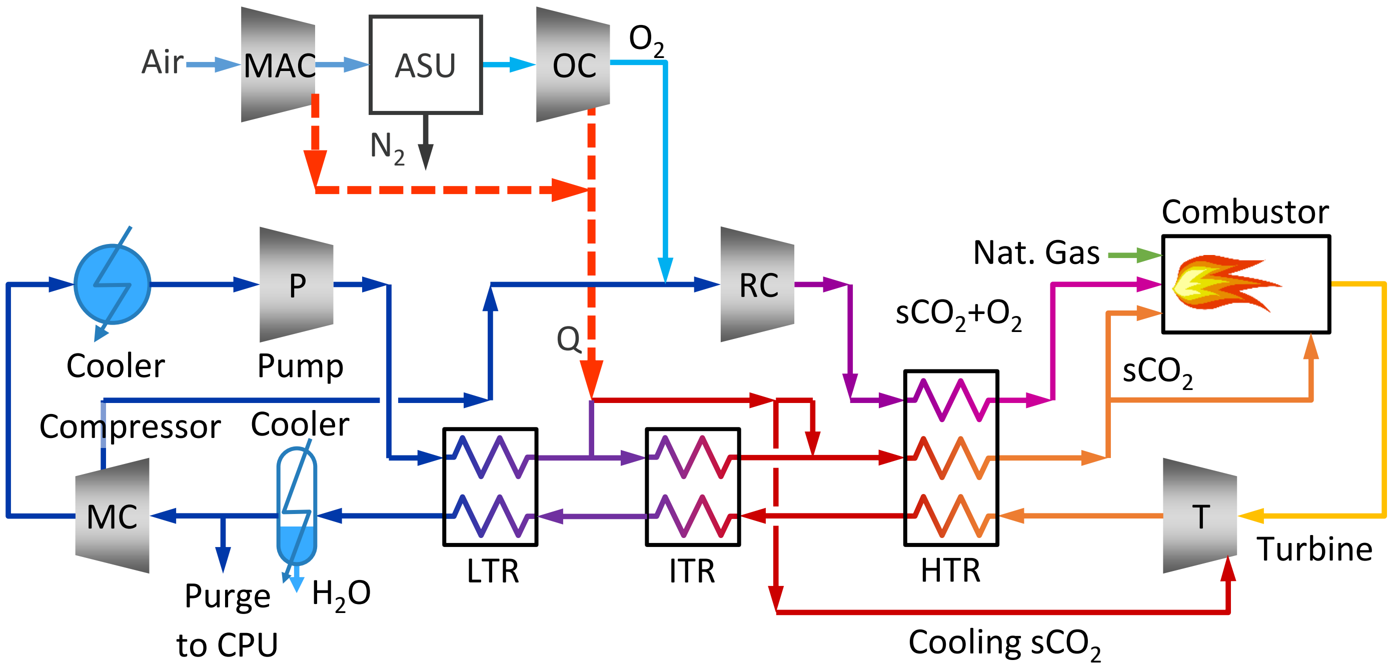
## Authors


- Eric Lewis, Deloitte
- Sydney Hughes, Leidos

# Analysis of Natural Gas Direct-Fired $sCO_2$ Power Cycle

- **<u>Objective</u>: Can NG direct $sCO_2$ plant can compete with NGCC CCS**

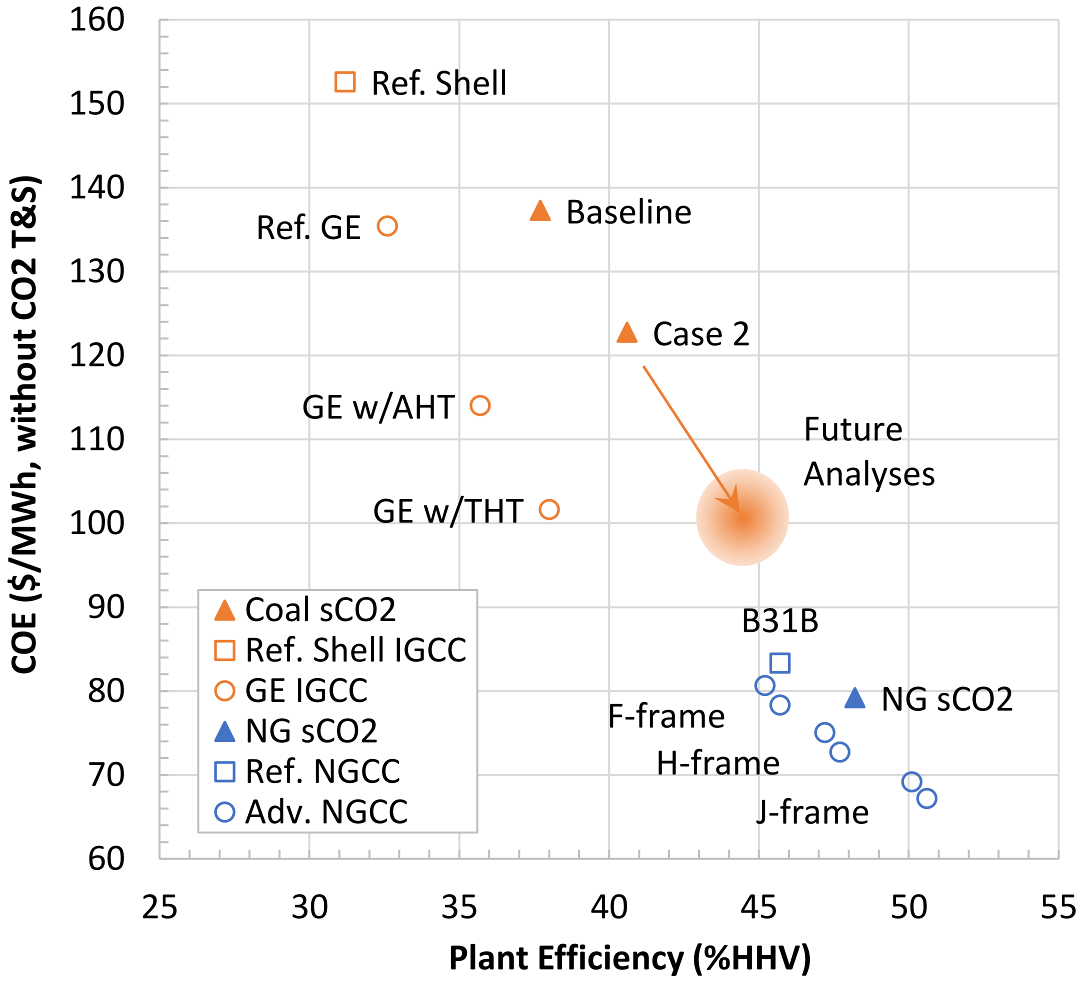
- **NG-direct $sCO_2$ plant design:**
  - Low pressure ASU with 99.5% purity
  - Thermal integration
  - Oxy-NG Combustor
  - Cooled $sCO_2$ turbine
  - Condensing $sCO_2$ cycle operation
  - CPU required for pipeline specs



# Direct $sCO_2$ Plant Comparisons

COE vs. Plant Efficiency Analysis, with CCS (IGCC & NGCC w/ CCS and Allam)

- **Direct sCO2 plants w/ Shell gasifiers - 20 % COE improvement over Shell IGCC system with CCS [1,2]**
- **NG direct $sCO_2$ cycle design includes thermal integration with ASU intercoolers and 3-stage recuperation train[3]**
  - NG $sCO_2$ plant HHV efficiency currently 48.2% with 99% carbon capture, with 3% lower COE than baseline NGCC plant with CCS (B31B)
  - Competitive with advanced turbine (F-frame, H-frame) NGCC cases with CCS and EGR




[1] 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.
[2] 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.
[3] Weiland, N.T., and White, C.W., "Performance and Cost Assessment of a Natural Gas-Fueled Direct sCO2 Power Plant," Report NETL-PUB-22274, 2019.

# NET Power
# 25 MWe Direct Fired $sCO_2$ Power Plant

NET Power's 25 MWe Allam cycle based power plant in La Port, TX; (a privately funded project).

Photographs by permission of Net Power, Circa 2017

## Status

- *Exelon, McDermott, Oxy Low Carbon Ventures, 8 Rivers & Toshiba*
- First-fire in May 2019
- Commissioning complete
- Operation underway

# Advanced Ultra-supercritical Component (ComTest) Project Update

## DOE Contract DE-FE0025064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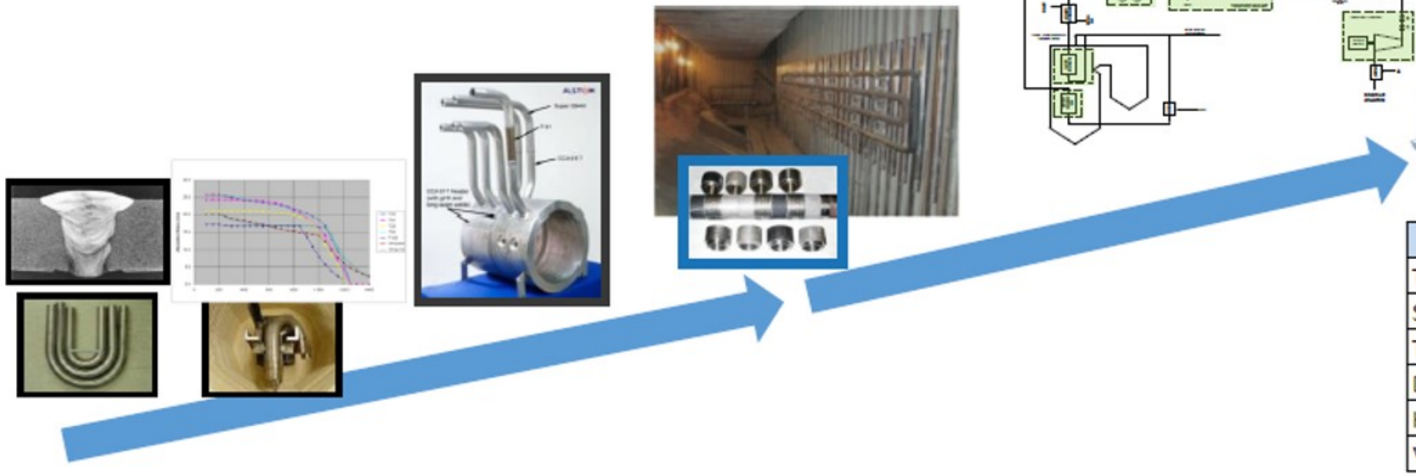
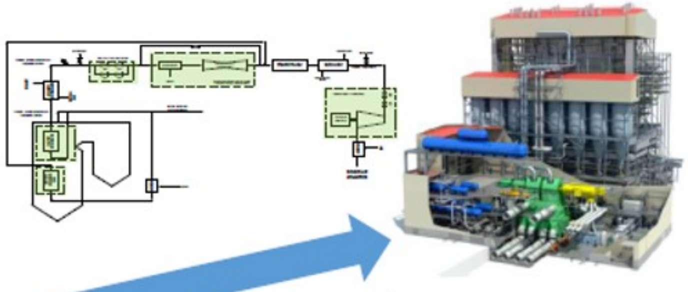
**Quarterly Review Meeting**
**Virtual Meeting – Session #1**
**March 2, 2021**


www.epri.com

# AUSC Commercialization Roadmap

| Technology Readiness Levels | | | Roadmap to AUSC Demo | |
|---|---|---|---|---|
| 2000 / 2005 | 2010 | 2015 | 2020 | 2025 |
| Materials Evaluation (Nickel Superalloy Focus) | Component Mockup | Steam Loop at Plant Barry. Large forgings & castings | AUSC Component Test (ComTest) | AUSC Demonstration |
| Laboratory TRL 2-3 | Proof of concept TRL 4 | Component Test TRL 4-5 | System TRL 4-7 | Overall TRL 8-9 |





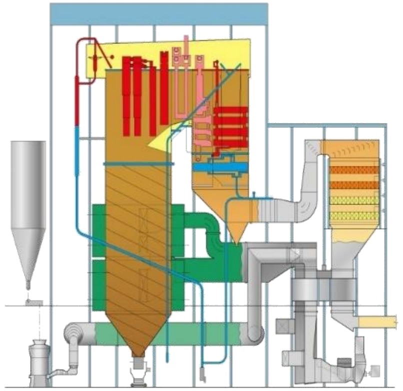
| Components | TRL |
|---|---|
| Tube Membrane Panel | 4 |
| Superheater | 5 |
| Turbine | 4 |
| Desuperheater | 4 |
| Header | 4 |
| Valves | 4 |

**Recently completed DOE-sponsored projects achieved TRL = 4/5**

**AUSC ComTest will achieve TRL = 7 (ready for full scale demo)**

# Tasks Completed in First 15 Years of DOE  AUSC Programs

Techno-Economics



Steamside Oxidation and Fireside Corrosion

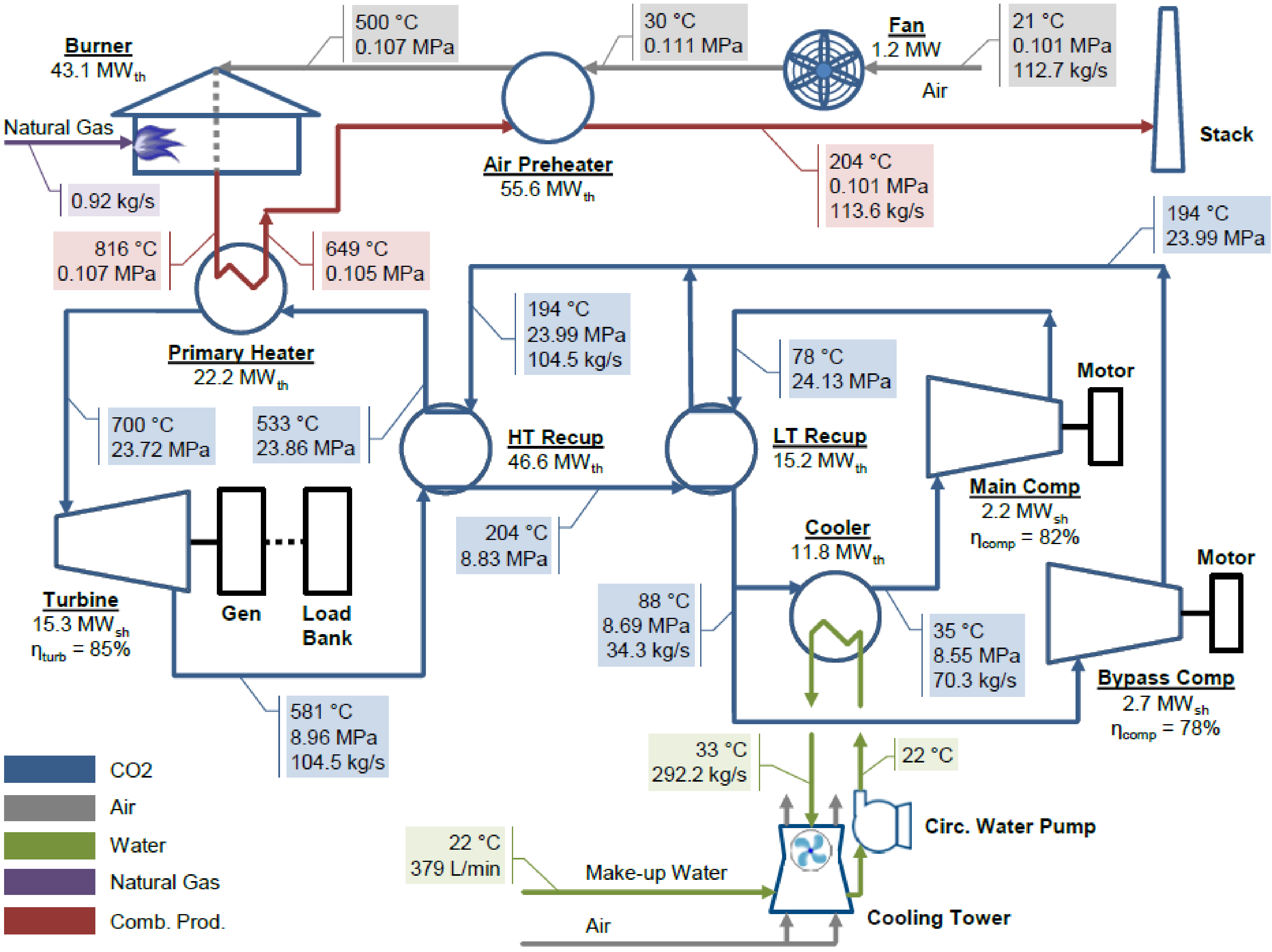
(Lab-Scale & In-Plant Testing)

Welding Technology Development

Nickel Superalloy Casting Development

Fabrication Processes

# Nominal 43 MWth Gas Fired Heater for the STEP Project




Ref: Techno-economic Analysis for a 10 MW Supercritical CO2 Pilot Plant, July 2015, DOE/NETL-2015/1701

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# Summary

Overview of DOE Energy Systems - Fossil Energy Power Systems

- **FE is developing two power cycles based on $sCO_2$**
  - Variations on the recompression Brayton cycle
  - Allam cycle
- **Advanced $sCO_2$ cycles and AUSC cycles will both depend on advanced materials**
- **FE has made considerable investment the ComTest consortium to deliver these advanced materials**
- **The STEP project is designed to demonstrate a pathway to a thermodynamic cycle efficiency greater than 50% and is currently one of the largest customers for the advanced alloys and welding techniques being discussed at this meeting**