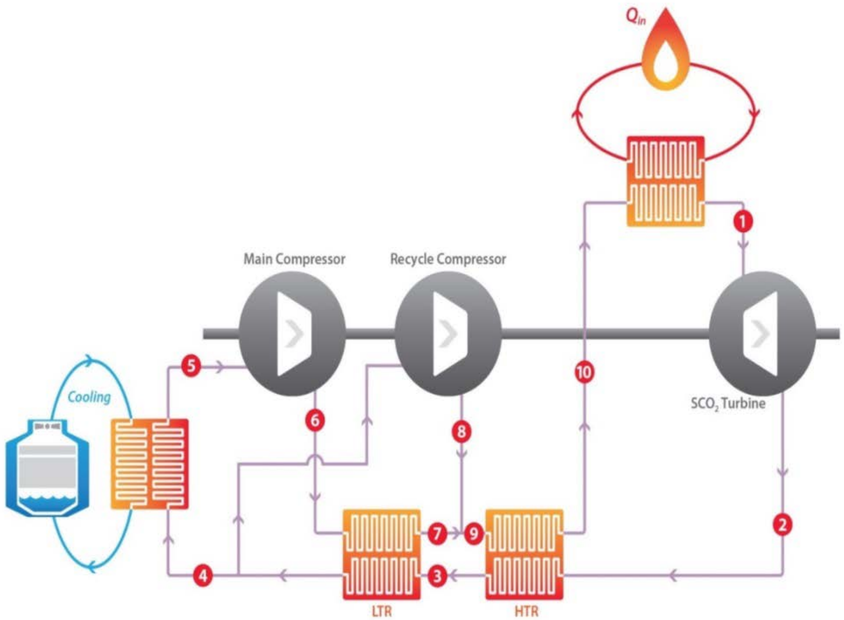

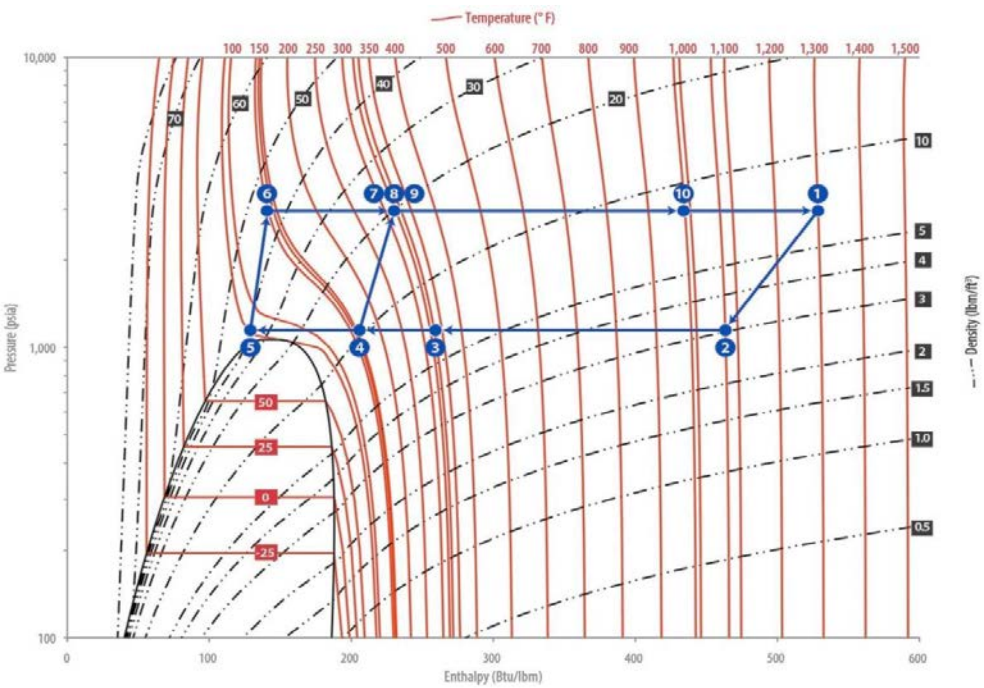

OXY-COAL-FIRED CIRCULATING FLUID BED COMBUSTION WITH A COMMERCIAL UTILITY-SIZE SUPERCRITICAL CO_2 POWER CYCLE

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Presentation Outline

- **Overall Plant Cycle: Oxy-Coal-Fired Circulating Fluid Bed (CFB) + Power Cycle**
  - *SOA (Commercially Available) SuperCritical (SC) Steam Rankine (3500 psig/1110°F/1150°F)*
  - *Recompression SuperCritical Carbon Dioxide (sCO_2) Brayton (~5000 psig /1148°F)*
  - *Advanced Ultra-SuperCritical (AUSC) Steam Rankine (3500 psig/1400°F/1400°F)*
- **Alternate sCO_2 Recompression Cycle Configurations**
  - *Reheat sCO_2 Case*
  - *Intercooled sCO_2 Case*
  - *Reheat and Intercooled Case*
- **Sensitivity Analyses to sCO_2 Operating Parameters**
  - *Overview of earlier sensitivity analysis*
- **Elevated Turbine Inlet Temperature Case (increases TIT to *1400°F)***
- **Summary and Conclusions**
- **Next Steps**
- **Acknowledgements**
  - Study Group, Generic Heat Source Cycles, NETL Programs

Site Characteristics and Design Coal

- Generic Midwestern U.S. Plant,
- ISO ambient conditions
- Illinois No. 6

Elevation, ft	0
Barometric Pressure, psia	14.696
Design Ambient Temperature, Dry Bulb, °F	59
Design Ambient Temperature, Wet Bulb, °F	51.5
Design Ambient Relative Humidity, %	60

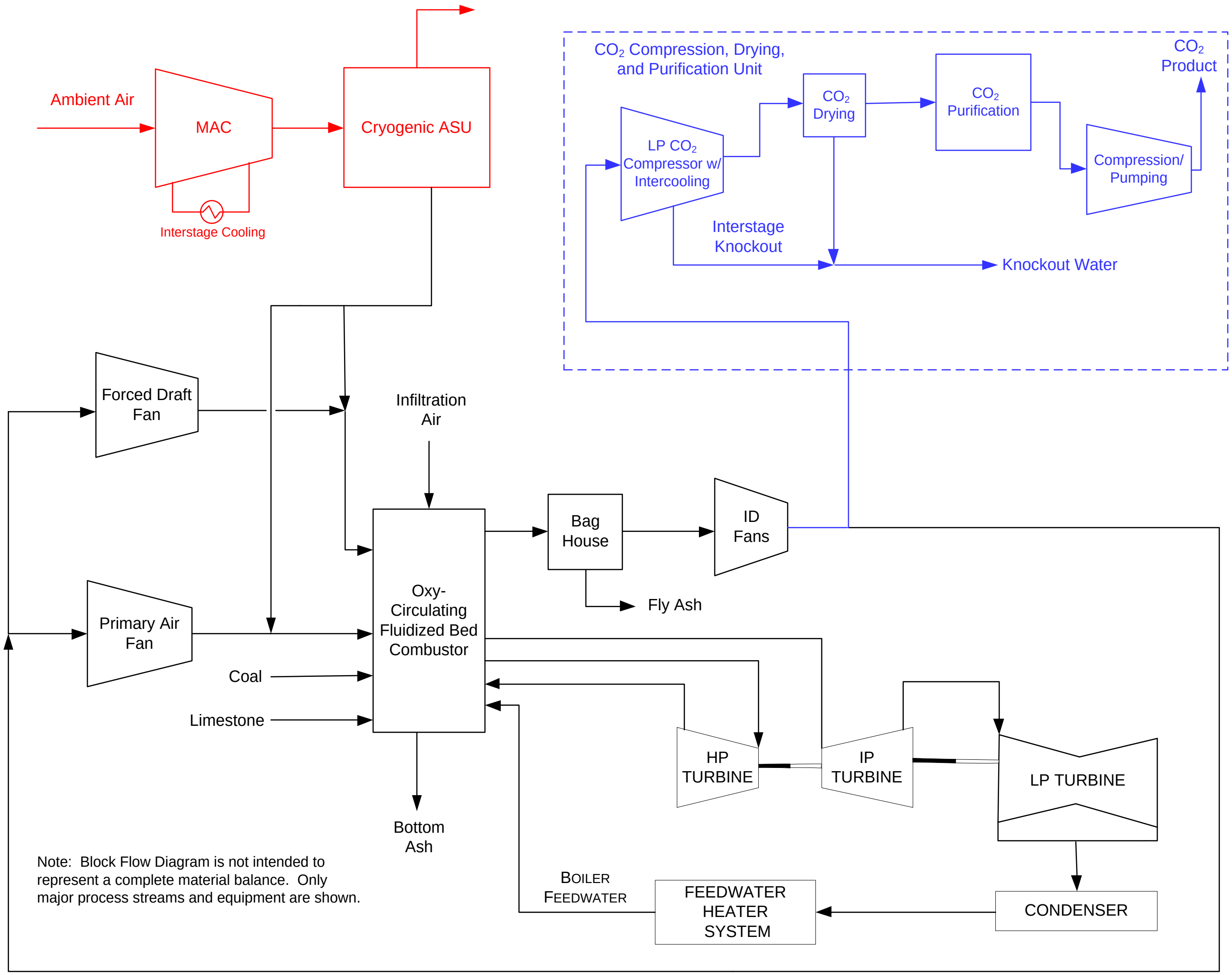
Location	A Greenfield site in the Midwestern United States[a]
Topography	Level
Size, acres	300
Transportation	Rail and Road
Ash Disposal	Off Site
Water	Municipal (50%) / Groundwater (50%)
Access	Land locked, having access by rail and highway
CO_2	Compressed to 15.3 MPa (2,215 psia), transported, and sequestered in a saline formation at a depth of 4,055 feet

[a]Champaign County, Illinois, is assumed for assessment of construction costs.

Coal name	Illinois No. 6	
ASTM D388 Rank	High Volatile A Bituminous	
Proximate Analysis	**As-received %**	**Dry %**
Moisture	11.12	0.00
Volatile Matter	34.99	39.37
Ash	9.70	10.91
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Ultimate Analysis	**As-received %**	**Dry %**
Carbon	63.75	71.73
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Sulfur	2.51	2.82
Chlorine	0.29	0.33
Ash	9.70	10.91
Moisture	11.12	0.00
Oxygen	6.88	7.74
Total	100.00	100.00
Reported Heating Value	**As-received Btu/lb (kJ/kg)**	**Dry Btu/lb (kJ/kg)**
HHV	11,666 (27,135)	13,126 (30,531)
LHV	11,252 (26,171)	12,660 (29,447)

Oxy-Coal-Fired Circulating Fluid Bed (CFB)

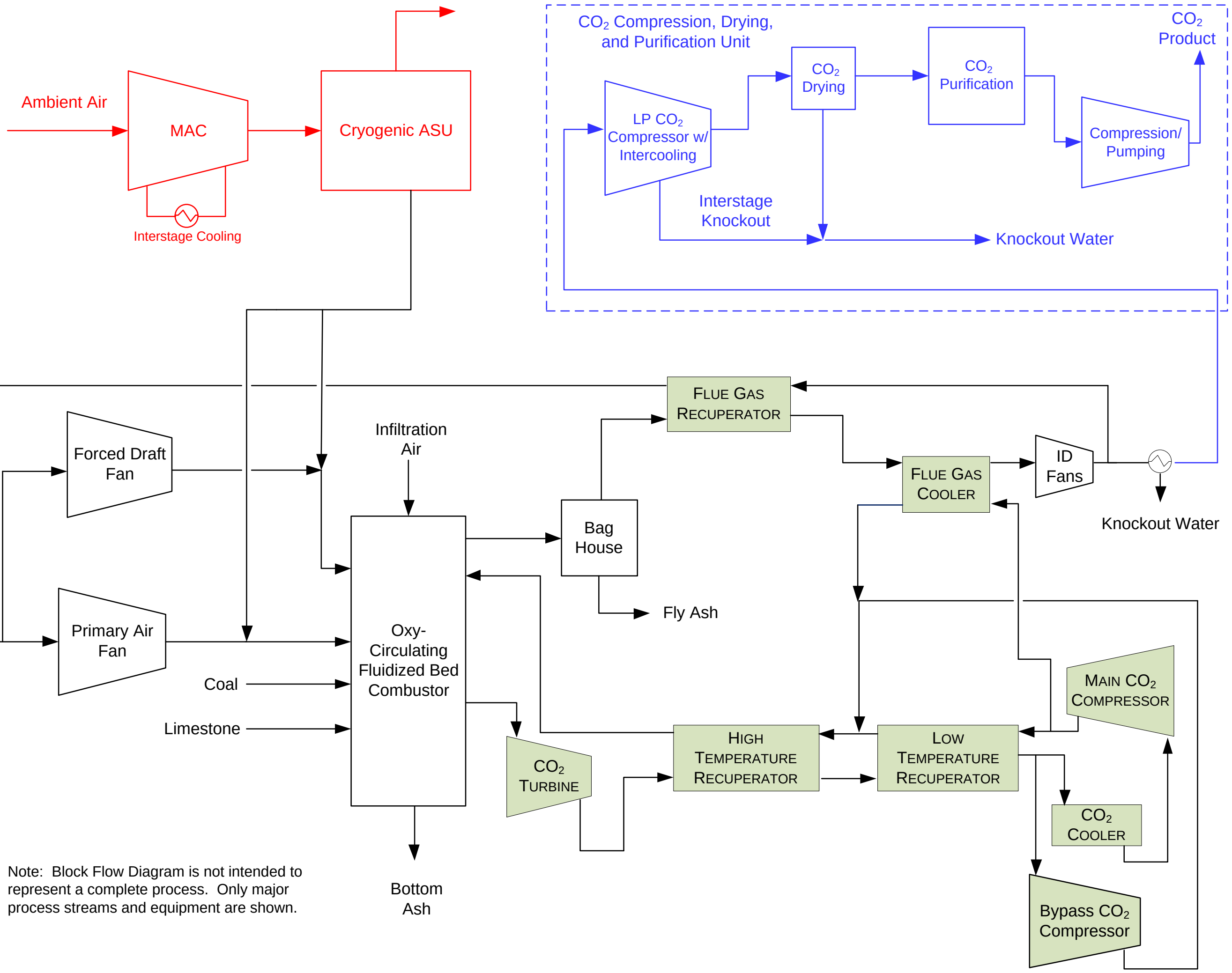
SOA SuperCritical (SC) Steam Rankine (3500 psig/1110°F/1150°F)



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

Oxy-Coal-Fired Circulating Fluid Bed (CFB))

Recompression SuperCritical Carbon Dioxide (sCO_2) Brayton (5000 psig / 1148°F)



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

Oxy-Coal-Fired Circulating Fluid Bed (CFB)

Recompression sCO_2 Brayton Cycle Parameters for Baseline Plant

Parameter	Value
Turbine Inlet Temperature	620 °C (1148 °F)
Nominal Compressor Pressure	5,015 psia
Turbine Exit Pressure	1,350 psia
Nominal Pressure Ratio	3.8
CO_2 Cooler Temperature	35 °C (95 °F)
Turbine Isentropic Efficiency	92.7 %
Compressor Isentropic Efficiency	85.0 %
Cycle Pressure Drop	60 psia
Minimum Temperature Approach	6 °C (10 °F)
Nominal CO_2 Cooler Bypass Fraction	To maximize recuperation

Oxy-Coal-Fired Circulating Fluid Bed (CFB)

Performance comparison between sCO_2 Brayton and Steam Rankine cycle plants

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	sCO2 Brayton Cycle (620 °C, 1148 °F)
CFB Coal Flow Rate (klb/hr)	484	489
CFB Coal Flow Rate/Limestone Flow Rate	4.1	4.1
Turb Flow Rate / Rankine Steam Turb Flow Rate	**1**	**9.9**
Coal Thermal Input (MWt)	1655	1670
Power Cycle Thermal Input (MWt)	1497	1528
Fractional Thermal Input to Power Cycle	0.905	0.915
Net Power Cycle Output	723	727
Total Auxiliary Power Load	173	177
Net Power Output	550	550
Power Cycle Efficiency (%)	**48.3**	**47.6**
Net Plant Efficiency (HHV %)	**33.2**	**32.9**

Alternate sCO_2 Recompression Cycle Configurations

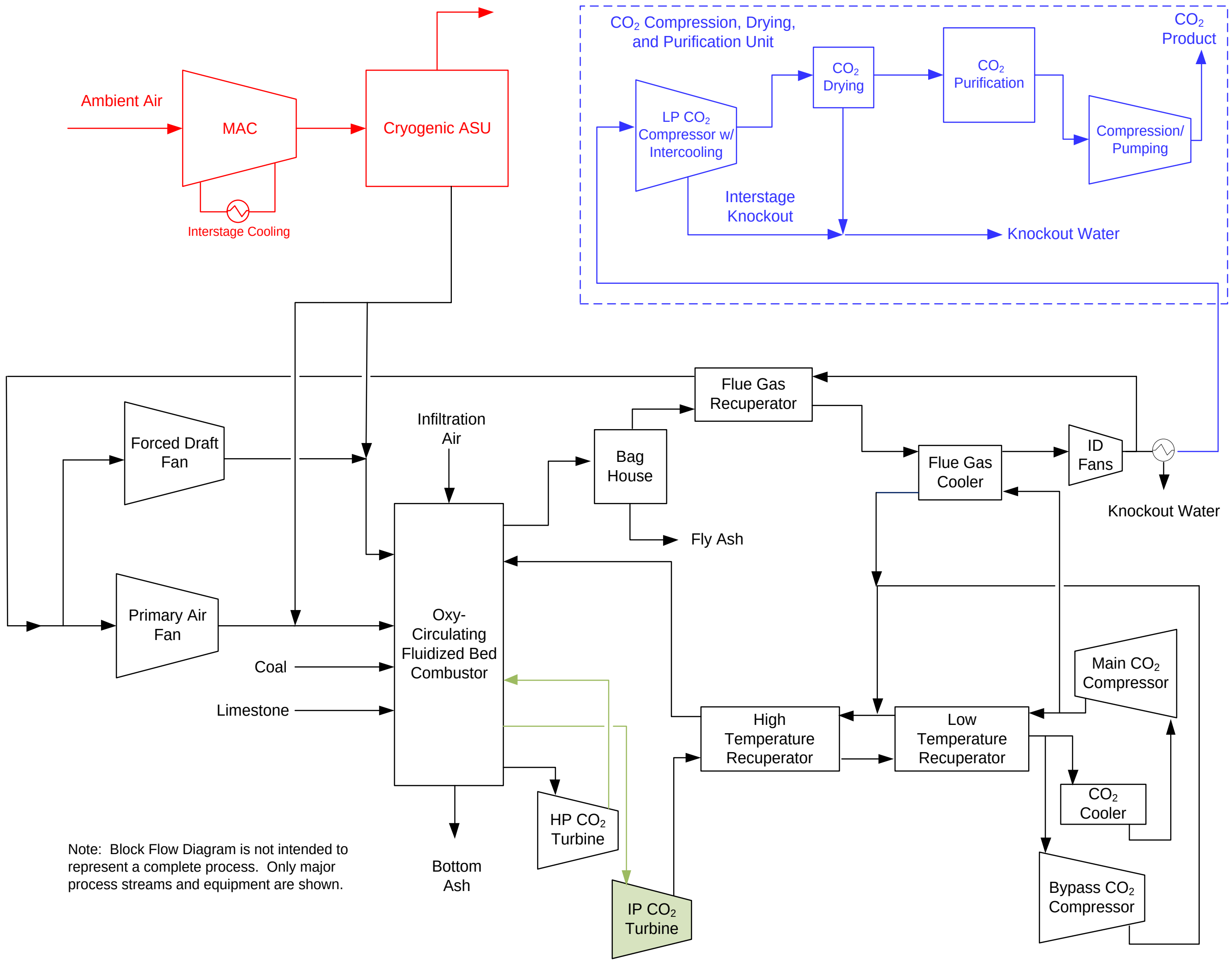
Objectives

- *Increase the fraction of plant thermal input that is captured in the sCO_2 cycle*
- *Increase the sCO_2 power cycle efficiency*
- *Decrease the sCO_2 plant auxiliary power requirement*
- *Provide some combination of above effects*

Alternate Cycles

- *Reheat sCO_2 Case*
- *Intercooled sCO_2 Case*
- *Reheat and Intercooled Case*

Alternate sCO_2 Recompression Cycle Configurations
Reheat sCO_2 Case



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

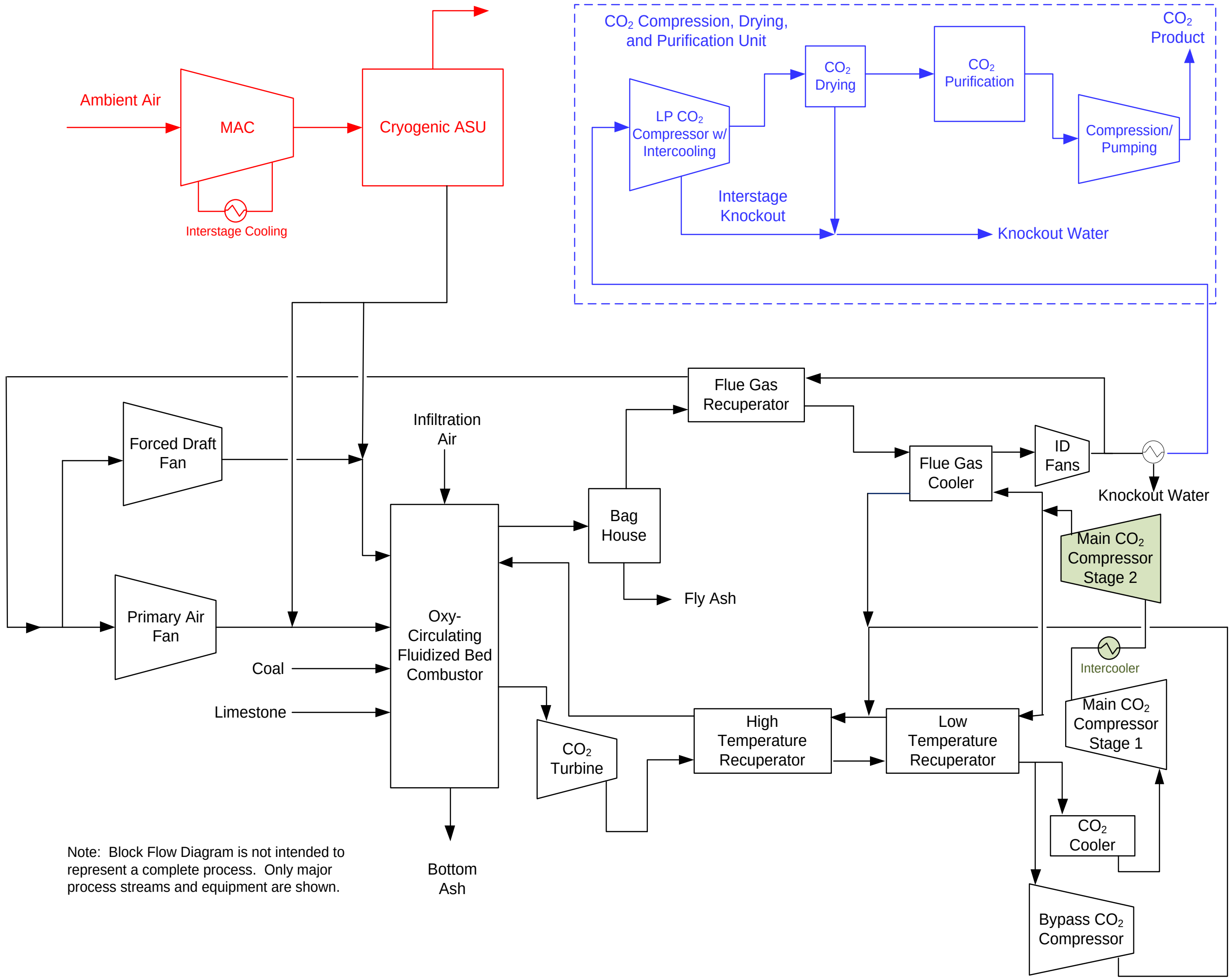
Alternate sCO_2 Recompression Cycle Configurations

Performance comparison between Rankine and Recompression sCO_2 Brayton cycles with and without reheat

Parameter	**Rankine Steam Cycle (593 °C, 1100°F)**	**Baseline sCO2 Brayton Cycle (620 °C, 1148 °F)**	**Reheat sCO2 Brayton Cycle (620 °C, 1148 °F)**
CFB Coal Flow Rate (klb/hr)	484	489	467
CFB Coal Flow Rate/Limestone Flow Rate	4.1	4.1	4.1
Turb Flow Rate / Rankine Steam Turb Flow Rate	**1**	**9.9**	**9.1**
Coal Thermal Input (MWt)	1655	1670	1597
Power Cycle Thermal Input (MWt)	1497	1528	1461
Fractional Thermal Input to Power Cycle	0.905	0.915	0.915
Net Power Cycle Output	723	727	719
Total Auxiliary Power Load	173	177	169
Net Power Output	550	550	550
Power Cycle Efficiency (%)	**48.3**	**47.6**	**49.3**
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**34.4**

Alternate sCO_2 Recompression Cycle Configurations

Intercooled sCO_2 Case



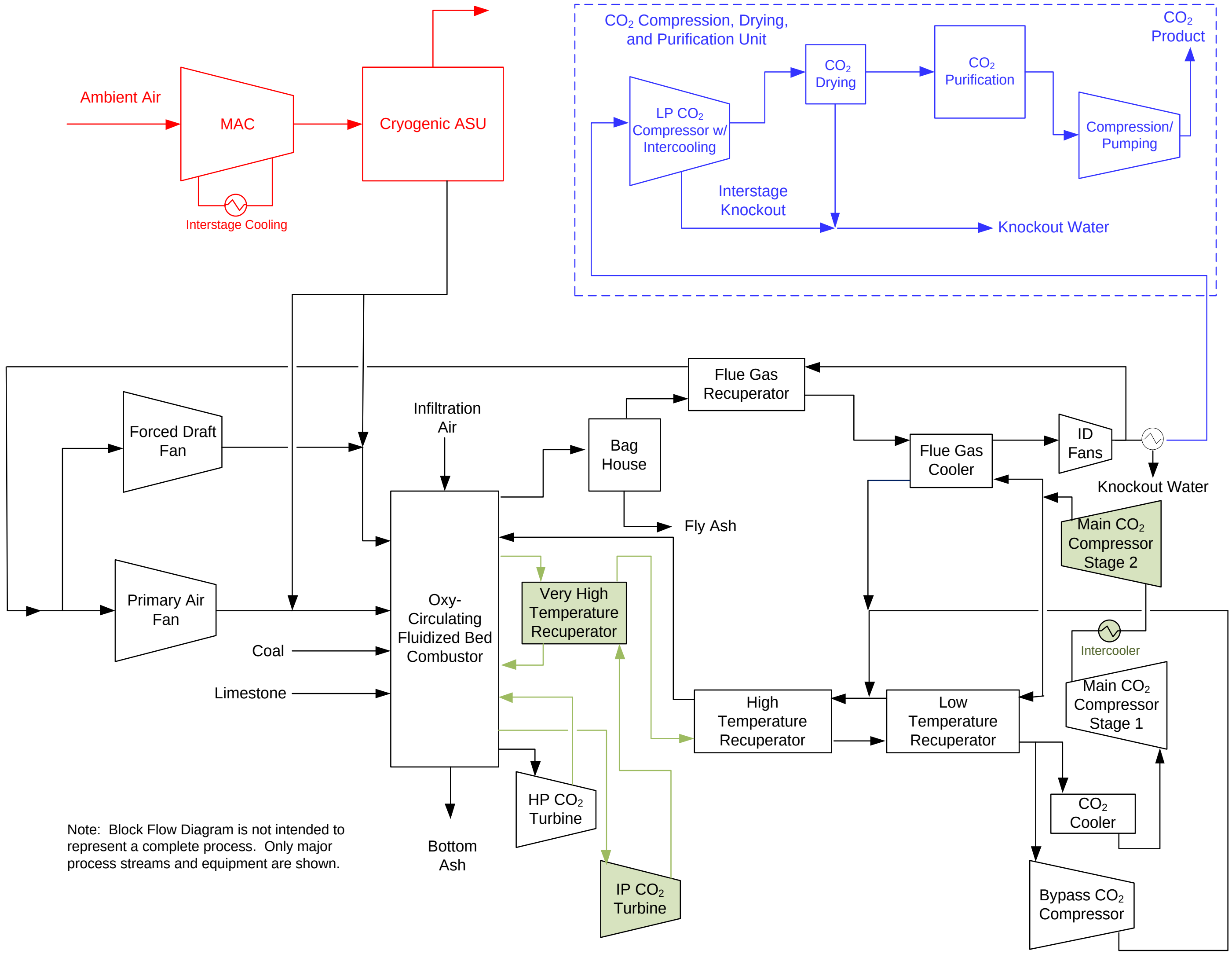
Note: Block Flow Diagram is not intended to represent a complete process. Only major process streams and equipment are shown.

Alternate sCO_2 Recompression Cycle Configurations

Performance comparison between Rankine and recompression sCO_2 Brayton cycles with and without main compressor intercooling

Parameter	Rankine Steam Cycle (593 °C, 1100°F)	Baseline sCO2 Brayton Cycle (620 °C, 1148 °F)	Intercooled sCO2 Brayton Cycle (620 °C, 1148 °F)
CFB Coal Flow Rate (klb/hr)	484	489	473
CFB Coal Flow Rate/Limestone Flow Rate	4.1	4.1	4.1
Turb Flow Rate / Rankine Steam Turb Flow Rate	**1**	**9.9**	**9.1**
Coal Thermal Input (MWt)	1655	1670	1619
Power Cycle Thermal Input (MWt)	1497	1528	1501
Fractional Thermal Input to Power Cycle	**0.905**	**0.915**	**0.927**
Net Power Cycle Output	723	727	722
Total Auxiliary Power Load	173	177	172
Net Power Output	550	550	550
Power Cycle Efficiency (%)	**48.3**	**47.6**	**48.1**
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**34.0**

Alternate sCO_2 Recompression Cycle Configurations
Reheat and Intercooled Case



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

Alternate sCO_2 Recompression Cycle Configurations

Performance comparison between Rankine, baseline sCO_2 recompression, and sCO_2 Brayton with reheat and main compressor intercooling

Parameter	Rankine Steam Cycle (593 °C, 1100°F)	Baseline sCO2 Brayton Cycle (620 °C, 1148 °F)	Reheat and Intercooled sCO2 Brayton Cycle (620 °C, 1148 °F)
CFB Coal Flow Rate (klb/hr)	484	489	457
CFB Coal Flow Rate/Limestone Flow Rate	4.1	4.1	4.1
Turb Flow Rate / Rankine Steam Turb Flow Rate	**1**	**9.9**	**8.5**
Coal Thermal Input (MWt)	1655	1670	1562
Power Cycle Thermal Input (MWt)	1497	1528	1448
Fractional Thermal Input to Power Cycle	**0.905**	**0.915**	**0.927**
Net Power Cycle Output	723	727	716
Total Auxiliary Power Load	173	177	166
Net Power Output	550	550	550
Power Cycle Efficiency (%)	**48.3**	**47.6**	**49.4**
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**35.2**

Sensitivity Analyses to sCO_2 Operating Parameters
Overview of earlier sensitivity analyses

- NETL – has conducted or reviewed multiple studies analyzing the performance of indirect cycles and the dependence on operating parameters. These studies examined the impact on cycle and system efficiencies for changes to operating parameters that include:
  - Turbine Inlet Temperature (TIT)
  - Maximum and minimum cycle pressures
  - CO_2 cooler temperature
  - Cycle pressure drop
  - Minimum approach temperature for recuperators
  - Turbo-machinery efficiencies

- Result – TIT exerts the strongest impact on cycle efficiencies

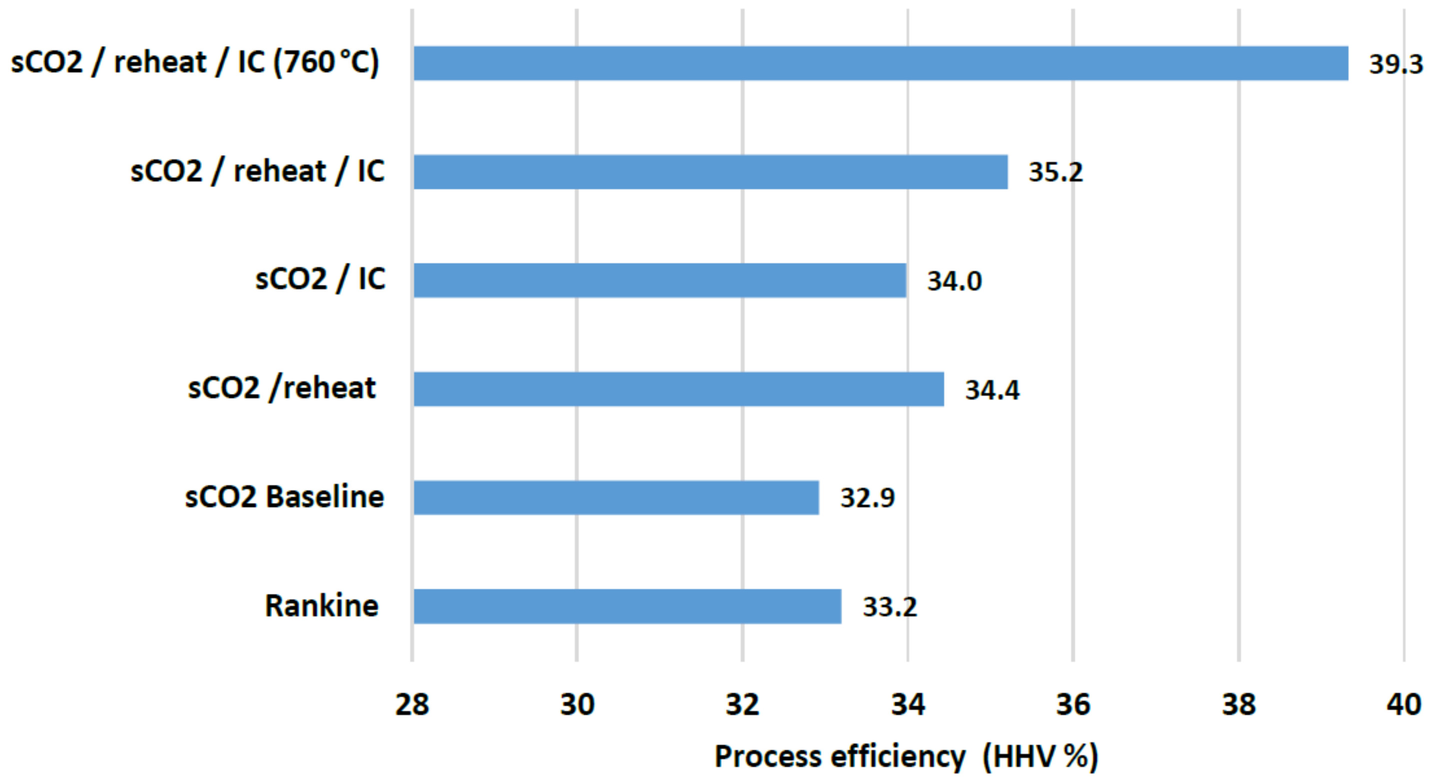
- Additional Case – changing the TIT from 620 °C, (1148 °F) to 760 °C, (1400 °F)

Alternate sCO_2 Recompression Cycle Configurations
Performance Comparison with Elevated Turbine Inlet Temperature Case

Parameter	**Rankine Steam Cycle (593 °C, 1100°F)**	**Reheat and Intercooled sCO2 Brayton Cycle (620 °C, 1148 °F)**	**Reheat and Intercooled sCO2 Brayton Cycle (760 °C, 1400 °F)**
CFB Coal Flow Rate (klb/hr)	484	457	409
CFB Coal Flow Rate/Limestone Flow Rate	4.1	4.1	4.1
Turb Flow Rate / Rankine Steam Turb Flow Rate	**1**	**8.5**	**6.8**
Coal Thermal Input (MWt)	1655	1562	1398
Power Cycle Thermal Input (MWt)	1497	1448	1296
Fractional Thermal Input to Power Cycle	**0.905**	**0.927**	**0.927**
Net Power Cycle Output	723	716	698
Total Auxiliary Power Load	173	166	148
Net Power Output	550	550	550
Power Cycle Efficiency (%)	**48.3**	**49.4**	**53.9**
Net Plant Efficiency (HHV %)	**33.2**	**35.2**	**39.3**

Summary and Conclusions

Overall Plant Efficiencies (% HHV)



Summary and Conclusions

- Objective - compare sCO_2 Recompression Brayton Cycle(s) to a SOA Steam Rankine Cycle.
- Performance determined for four configurations, all showing performance improvement.
- At the lower temperature (620 °C, 1100 °F), the most comparable sCO_2 Case (reheat and intercooled) to the Steam Rankine Case shows improvement in overall process efficiency of ~ 2 percentage points.
- At the higher temperature (760 °C, 1400 °F), the comparison to the Steam Rankine Cycle (620 °C, 1100 °F) improves in overall efficiency to ~ 6 percentage points.
- Further optimizations of the configurations considered may be required to demonstrated an economic advantage.

Next Steps

- **Advanced Ultra-SuperCritical (AUSC) Steam Rankine Case**
  - (3500 psig/1400°F/1400°F)
- **Economic Analysis**
  - Information from NETL sponsored programs + other sources for
  - Component costs for key sCO_2 Cycle Components
  - Cost sensitivity studies for key components
- **Alternate Cycles**
  - *Direct sCO_2 Cycles based on coal*
  - *Hybrid Cycles, Cascade Cycles*
  - *Condensing CO_2 Cycles*
- **Possible designs for pilot/demo plants**

Acknowledgements

- **Study Group:**
  - *Charles White, John Plunkett, David Gray (ESPA/Noblis Inc.)*
  - *Walter Shelton, Nathan Weiland (NETL/DOE)*
- **Generic Heat Source sCO_2 Cycles**
  - *White, C., Shelton, W., Dennis, R. (2014, September 9-10). An Assessment of Supercritical CO_2 Power Cycles Integrated with Generic Heat Sources. 4th International Symposium – Supercritical CO_2 Power Cycles: Pittsburgh, Pennsylvania.*
- **PFBC sCO_2 Cycles**
  - *G. Subbaraman, J. A. Mays, B. Jazayeri, K. M. Sprouse, A. H. Eastland, S. Ravishankar and C. G. Sonwane, Energy Systems, Pratt and Whitney Rocketdyne, ZEPS Plant Model: A High Efficiency Power Cycle with Pressurized Fluidized Bed Combustion Process, 2nd Oxyfuel Combustion Conference, Queensland, Australia, September 2011.*
- **NETL Programs / Financial Support**
  - *sCO_2 Component Development (references 1 – 8 of conference paper)*
  - *Material Research and Thermodynamic Properties (e.g. programs with ORNL)*
  - *NETL Internal sCO_2 System Studies (indirect and direct cycles, STEP program, reviews of literature studies)*

Questions ??

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