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

Walter W. Shelton
Engineer
U.S. DOE - NETL
Morgantown, WV U.S.
Walter.Shelton@NETL.DOE.GOV

Nathan Weiland
Engineer
U.S. DOE - NETL
Pittsburgh, PA U.S.
Nathan.Weiland@NETL.DOE.GOV

Charles White
Senior Principal
Noblis, Inc.
Falls Church, VA U.S.
Charles.White@noblis.org

John Plunkett
Principal
Noblis, Inc.
Falls Church, VA U.S.
John.Plunkett@noblis.org

David Gray.
Senior Principal
Noblis, Inc.
Falls Church, VA U.S.
David.Grey@noblis.org

Walter Shelton is an engineer in the Systems Engineering & Analysis group at the National Energy Technology Laboratory (NETL) supporting research/process development projects. Focused on the analysis and development of processes based on fossil fuels spanning both existing and emerging technologies that produce electrical power or a combination of power and chemicals. Key aspects involve performing system process studies that determine the efficiency, economic, regulatory, and environmental impacts. The process studies are targeted to contribute to formulating and determining government/public policy. He received a BS (SUNYAB) and MS (University of Minnesota) in Chemical Engineering.

Dr. Nathan Weiland is an engineer in the Systems Engineering & Analysis group at NETL, where he performs systems studies of supercritical CO_2 power cycles and oxy-fuel magneto-hydrodynamics (MHD) power plants. Prior to joining the systems analysis group he was a Research Professor at West Virginia University, where he worked with NETL on low-NOx hydrogen combustion, coal/biomass co-gasification, ash deposition processes in gasification systems, oxy-combustion plasmas for MHD power, and chemical looping combustion. He has received a BS (Purdue University), MS, and PhD (Georgia Tech) in Mechanical Engineering.

Charles White is a senior principal engineer at Noblis, where he performs modeling, simulation, and systems analysis of fossil-fueled processes for producing electric power and transportation fuels. He has provided energy systems analysis modeling and simulation support to NETL since 1985. He received a PhD in chemical engineering from the University of Pennsylvania.

John E. Plunkett is a principal engineer at Noblis, where his interests include fossil energy power generation and environmental clean-up. He received an MS in chemical engineering from the University of Delaware.

Dr. Gray is a senior principal engineer at Noblis. He has extensive experience in conversion of coal into electric power, fuels and chemicals and has provided research and development (R&D) guidance to NETL in those areas for many years. Prior to coming to the U.S. he worked in South Africa where he was an R&D manager operating pilot plants for alternative transportation fuels production. He has served on the National Academies of Sciences Committee on America's Energy Future and as a subject matter expert on the National Petroleum Council Study on Future Transportation Fuels. He received a PhD in physical chemistry from the University of Southampton in the United Kingdom.

ABSTRACT

Indirect (closed) supercritical carbon dioxide (sCO_2) Brayton cycles integrated with a variety of thermal heat sources (e.g., nuclear, concentrated solar, fossil, waste heat) have received increased attention due to the potential cycle efficiency advantage compared to steam Rankine cycles at similar turbine inlet temperature and pressure conditions. The efficiency benefit largely results from the recuperation of the high-quality heat from the sCO_2 turbine exhaust, which effectively preheats the CO_2 entering the heat source, although these benefits are offset to some degree by higher compressor power requirements.

The subject of this study is an indirect sCO_2 Brayton cycle combined with an oxy-coal circulating fluid bed (CFB) heat source and carbon capture and storage (CCS). The CFB—modified with enhanced combustion oxidant preheating—provides an advantage of a nearly-constant temperature heat source for the sCO_2 working fluid. The CO_2 is captured from the oxy-combustion process by condensing out water and sending the concentrated CO_2 stream to a standard CO_2 purification unit (CPU), followed by compression to 2200 psig for storage as part of enhanced oil recovery (EOR) or in a saline formation. Performance data for a baseline recompression Brayton cycle will be presented, with comparisons to an oxy-CFB supercritical Rankine cycle system. Alternative cycle configurations and options for integrating the sCO_2 cycle with the other plant processes in pursuit of higher performance will also be presented.

1 Introduction and Background

The United States (U.S.) Department of Energy's (DOE) Clean Coal and Carbon Management Program (CCCMP) provides a worldwide leadership role in the development of advanced fossil fuel-based energy conversion technologies, with a focus on electric power generation with carbon capture and storage (CCS). As part of DOE's Office of Fossil Energy (FE), the National Energy Technology Laboratory (NETL) implements research, development, and demonstration (RD&D) programs that address the challenges of reducing greenhouse gas emissions. To meet these challenges, FE/NETL evaluates advanced power cycles that will maximize system efficiency and economic performance, while minimizing CO_2 emissions and the costs of CCS.

NETL is addressing supercritical carbon dioxide (sCO_2) indirect power cycle research and development (R&D) needs cooperatively with other DOE Offices (Nuclear Energy (NE), and Energy Efficiency and Renewable Energy (EERE)). NETL conducts R&D for indirect and direct cycles in-house and by working with motivated industrial/academic partners through NETL-administered financial assistance. Recent cooperative agreements (1)-(8) are aimed at developing equipment components (e.g., turbomachinery, recuperators, oxy-fuel combustors/boilers, materials) that both internal and external studies have identified as currently available only at low technical readiness levels (TRL).

The indirect cycles that use sCO_2 in a closed loop as the working fluid have the advantage of using a wide range of thermal heat sources (e.g., nuclear, concentrated solar, fossil, waste heat). This results in the power plant design being dependent on the temperature of this thermal heat source with the overall efficiency usually increasing with temperature. System analysis studies by a number of research organizations including NETL have projected efficiency improvements of 2 – 6 percentage points when compared with Rankine cycles operating at similar process conditions. Direct cycles are based on incorporating fossil fuel combustion that heats a large flowrate of recirculating sCO_2, which acts as a diluent in a semi-closed cycle that removes the generated CO_2 for storage as part of enhanced oil recovery (EOR) or in a saline formation. For these cycles, the range of operating parameters (temperature, pressure) can vary considerably compared to indirect cycles. An additional question for direct cycles that use coal-derived syngas is how to remove contaminants from the combustion process that occurs at high pressure and temperature conditions.

As part of NETL's systems analysis efforts, an earlier study provides a sensitivity analysis for the indirect sCO_2 recompression Brayton cycle for demonstrating and examining the potential benefits, which include the potential for higher efficiency, high power density (more compact) equipment, reduced capital costs, and emissions reductions compared to steam based power cycles (9). This study, based on a generic heat source, was used as the basis for the current work, integrating the recompression cycle with a coal fueled oxy-combustion CFB at a nominal power plant size of 550 MWe. NETL has reviewed this type of system in an earlier funded program for which NETL suggested a number revisions and improvements (10).

The power plants in this study where modeled using Aspen Plus® (Aspen) and are assumed to be located at a generic plant site in Midwestern U.S. at zero elevation and with ambient conditions that are the same as International Organization for Standardization (ISO) conditions, i.e., barometric pressure 14.7 psi (0.10 MPa), dry bulb and wet bulb temperatures of 59 °F (15 °C) and 52 °F (11 °C), respectively, and 60 percent relative humidity. The fuel source selected for the power plant in this study is Illinois No. 6 bituminous coal, which is used as a reference fuel in many of NETL's systems studies (11), (12). For the most part, coal-based power plants can attain a higher plant efficiency using bituminous coal than by using lower rank coals.

A baseline case was developed with moderate temperature conditions of 1148 °F (620 °C) for the sCO_2 turbine expander inlet temperature. This case is compared to a reference oxy-combustion Rankine cycle that represents current technology. Additional cases are used to examine possible improvements to the baseline recompression cycle that include adding a reheat section, using main compressor intercooling, and a case that includes both of these modifications. The cases are still being developed to look for additional modifications that could lead to further efficiency improvements. A final case was developed at an aggressive sCO_2 turbine expander inlet temperature of 1400 °F (760 °C).

2 Reference Oxy-Coal-Fired Rankine Case

Figure 1 shows a block flow diagram (BFD) for the oxy-coal-fired Rankine power plant (13). The oxy-CFB plant has a net plant output of 550 MW and an overall higher heating value (HHV) plant efficiency of 33.2 percent. A cryogenic air separation unit (ASU) supplies the O_2 (95 mole percent O_2) required to combust coal in the CFB combustor, which generates the supercritical steam that drives a steam generator to produce electric power. Limestone is injected into the CFB combustor bed to remove sulfur present in the coal. A combination of solids recycle rate and single-pass carbon conversion is used to maximize the overall carbon conversion in the CFB. A high solids recycle rate is used to give an overall carbon conversion of ~99 percent. The CFB heat loss is assumed to be 1 percent of the thermal input of the coal.

The flue gas from the CFB combustor passes through a bag house to remove particulate matter and is split into two streams. A portion of the flue gas stream (45 percent) is recirculated to the CFB to maintain CFB operating temperature of 1,600 °F and the remaining exhaust flue gas is sent to the CO_2 purification unit (CPU). The CPU purifies the CO_2 product stream to obtain a CO_2 purity of 95 percent or greater, and a maximum O_2 content of 10 ppmv to comply with EOR O_2 content specification. The CPU also compresses the CO_2 to a pressure of 2,200 psi. The feed to the plant is Illinois No. 6 coal. A single reheat Rankine supercritical steam cycle at steam conditions: 3,500 psig/1,100 °F/ 1,100 °F (24.1MPa/ 593 °C/ 593 °C) is used to generate power.

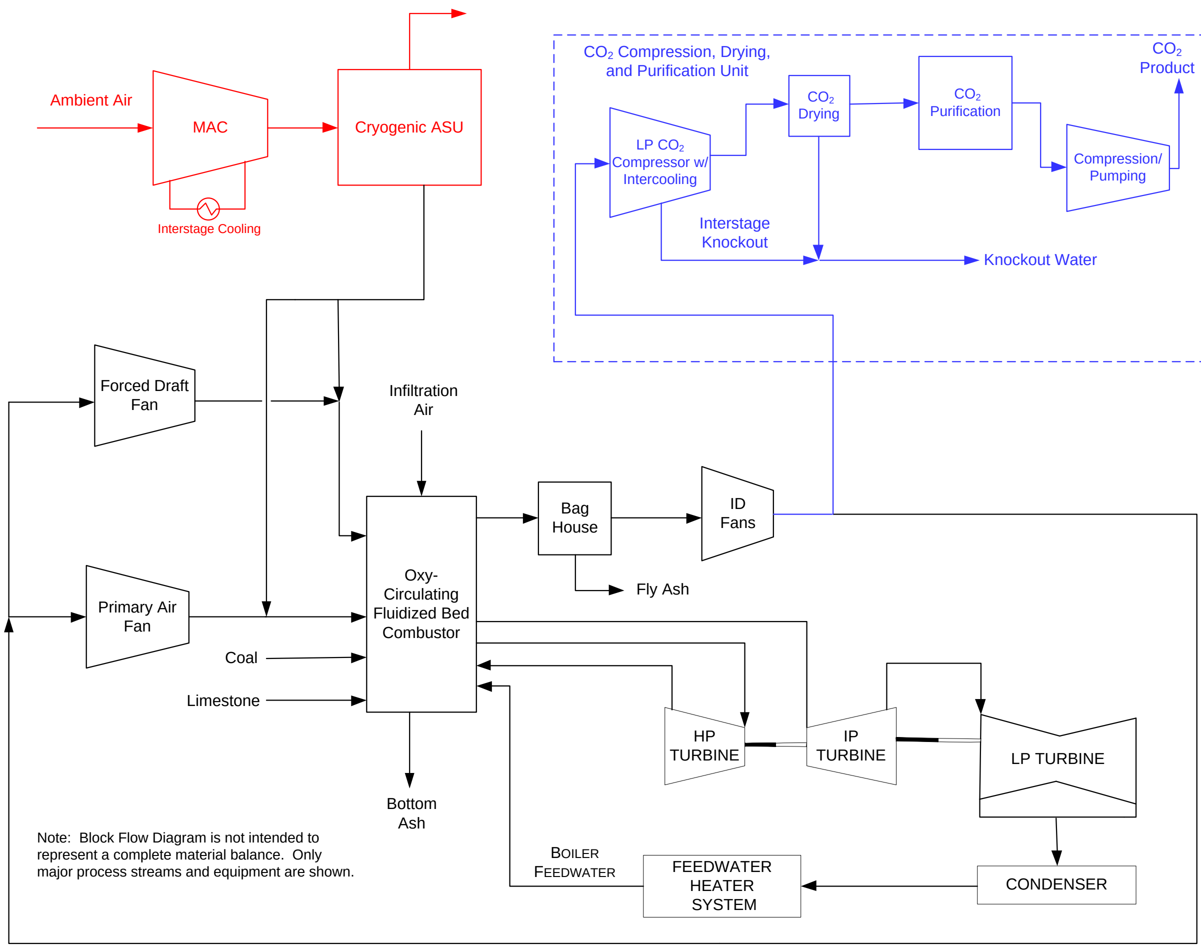

Figure 1 Reference oxy-coal-fired Rankine power plant

3 Baseline Oxy-Coal-Fired sCO_2 Recompression Brayton Cycle

Figure 2 shows a BFD for the oxy-coal-fired baseline sCO_2 recompression Brayton cycle power plant. The performance of this conceptual commercial plant is based on an Aspen simulation of the process. Illinois No. 6 coal is fed to the atmospheric pressure CFB together with limestone that is added for sulfur capture. Oxygen is provided by a low pressure (LP) ASU. A circulating stream of CO_2 provides fluid bed mixing in the CFB. The same bed temperature as the reference plant of 1,600 °F, the same carbon conversion (~99 percent), and the same heat loss (1 percent) is used. The CFB heats sCO_2 that flows through boiler tubes. This indirectly heated sCO_2 carries heat to the power cycle, whereas supercritical steam is used in the reference plant. Flue gas from the CFB is cooled and condensate is removed in a water knockout tank. A portion of the flue gas, which consists primarily of CO_2, is recycled to the CFB as a fluidizing gas. Unlike in the reference Rankine plant, the recycle CO_2 passes through a recuperator where the raw CFB flue gas heats it to approximately 980 °F.

The remainder of the dried flue gas is fed to the CPU, which operates at the same conditions and under the same specifications as the CPU used in the reference Rankine plant.

The CO_2 power cycle is analogous to a steam bottoming cycle, except that the working fluid is CO_2 rather than H_2O. Supercritical (~5,000 psig) CO_2 is heated to 1,148 °F in the boiler and is expanded in the turbine for power generation. The pressure ratio of the CO_2 expander is on the order of 3 to 4. Exhaust CO_2 from the expander is cooled in recuperators. The CO_2 stream is then separated into two portions; one is cooled and recompressed, and the other bypasses the cooler and is recompressed.

The pressurized CO_2 stream that passed through the CO_2 cooler is split into two streams; one portion passes through the cold side of the low temperature recuperator (LTR) and the other portion passes through the cold side of the flue gas heat exchanger. Both streams are heated to the same temperature before joining with the compressed CO_2 bypass stream and entering the high temperature recuperator (HTR). The CO_2 exiting the cold side of the HTR then passes through the CFB for further heating to the turbine inlet temperature (TIT) of 1,148 °F.

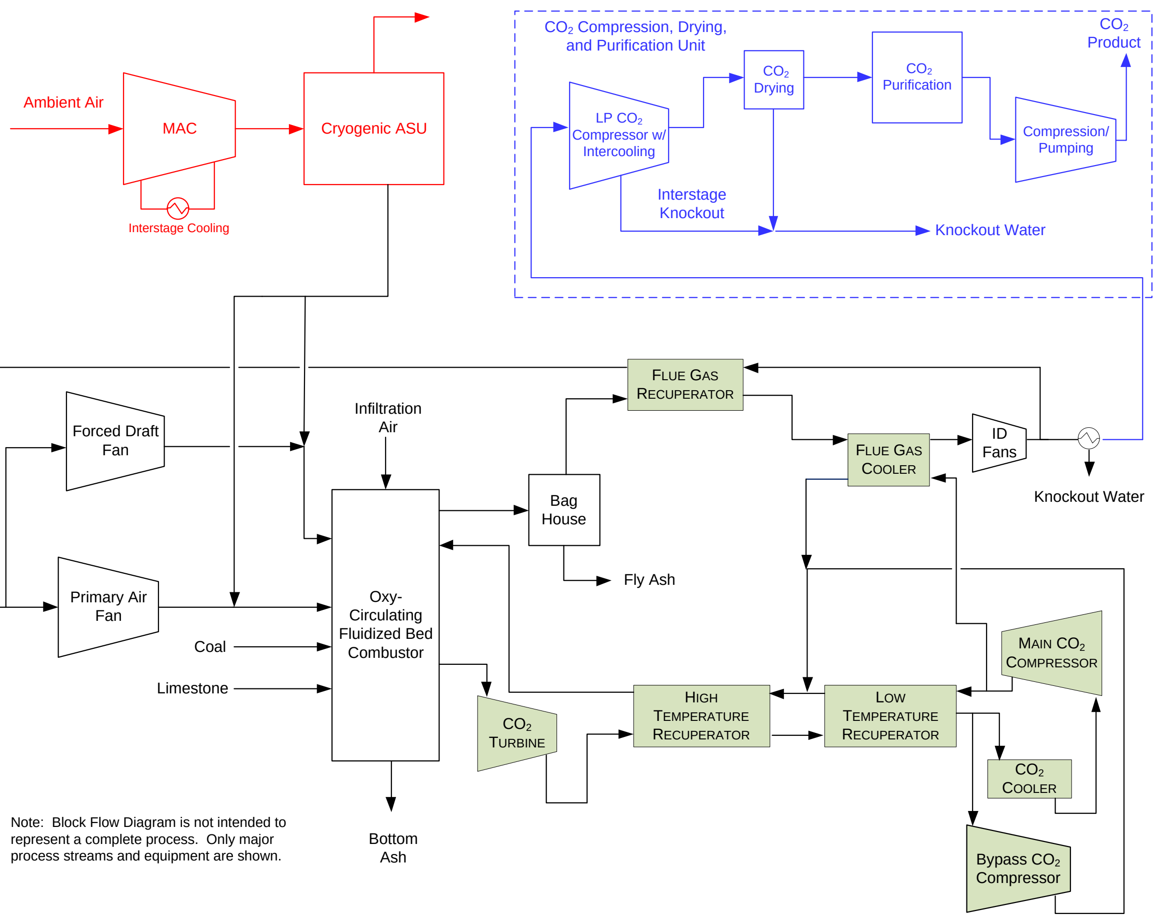

Figure 2 Block flow diagram for the baseline sCO_2 recompression Brayton cycle

The flue gas cooling schema that includes the flue gas recuperator and the flue gas heat exchanger recovers a large fraction of the sensible heat in the flue gas for the sCO_2 power cycle and obviates the need for a bottoming cycle.

Table 1 shows the operating parameters for the baseline sCO_2 Brayton cycle configuration. The sCO_2 TIT was 620 °C (1,148 °F) and the inlet pressure was 4,970 psig (equal to the CO_2 compressor outlet pressure less the pressure drops through the recuperators and CFB). The sCO_2 turbine pressure ratio was 3.7, which resulted in an exit pressure of 1,350 psia. The fraction of the CO_2 cooler bypass was chosen to maximize recuperation.

Table 1 Baseline sCO_2 Brayton cycle parameters

Parameter	Value
Turbine Inlet Temperature	620 °C (1,148 °F)
Compressor Outlet Pressure (psig)	5,000
Turbine Exit Pressure (psia)	1,350
Nominal Compressor Pressure Ratio	3.8
CO_2 Cooler Temperature	35 °C (95 °F)
Turbine Isentropic Efficiency	0.927
Compressor Isentropic Efficiency	0.85
Cycle Pressure Drop (psia)	60
Minimum Temperature Approach	6 °C (10 °F)
Nominal CO_2 Cooler Bypass Fraction	To maximize recuperation

It should be noted that the baseline sCO_2 recompression cycle plant is a relatively simple configuration and does not reflect the maximum potential of an indirect-fired sCO_2 power plant. Similarly, the parameters in Table 1 are based on a systems analysis of a sCO_2 recompression cycle (9) and are not intended to represent an optimum operating point for an integrated plant. Rather, the baseline process and operating point serve as a starting point from which to develop a more advanced and more efficient conceptual plant design.

4 Performance Comparison between Reference Rankine and Baseline sCO_2 Case

Table 2 shows the performance comparison between the oxy-fired CFB supercritical steam Rankine cycle and the 1,148 °F baseline sCO_2 Brayton cycle power plants.

Table 2 Performance comparison between sCO_2 Brayton and Rankine cycle plants

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	sCO_2 Brayton Cycle (620 °C, 1148 °F)
CFB Coal Flow Rate (lb/hr)	483,994	488,528
Limestone Flow Rate (lb/hr)	116,535	117,729
Oxygen Flow Rate (lb/hr)	1,034,064	1,045,070
sCO_2 Flow Rate (lb/hr)	---	43,395,000
Net Plant Efficiency (HHV %)	**33.2**	**32.9**
HHV Heat Rate (Btu/kWh)	10,267	10,363

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	sCO_2 Brayton Cycle (620 °C, 1148 °F)
sCO_2 Power Cycle Efficiency (%)	---	**47.6**
sCO_2 Cycle Heat Rate (Btu/kWh)	---	7,167
Steam Power Cycle Efficiency (%)	**48.3**	---
Steam Cycle Heat Rate (Btu/kWh)	7,069	---
Coal Thermal Input (MMBtu/hr)	5,646	5,699
Power Cycle Thermal Input (MMBtu/hr)	5,109	5,214
Fractional Thermal Input to Power Cycle	0.905	0.915
Raw Water Withdrawal (gpm)	9,127	9,877
Power Summary (kW)		
Steam Turbine Power Output	722,836	0
sCO_2 Turbine Power Output	0	727,460
Gross Power Output	722,836	727,460
Total Auxiliary Power Load	172,851	177,464
Net Power Output	549,985	549,996

Referring to Table 2, the net plant HHV efficiency for the sCO_2 cycle is 0.3 percentage points lower than the steam Rankine cycle plant, despite the fact that the sCO_2 power cycle is able to utilize a greater fraction of the plant thermal input than is the Rankine power cycle. The lower process efficiency of the baseline sCO_2 plant compared to the reference Rankine plant is due both to the lower power cycle efficiency for the sCO_2 Brayton cycle compared to the Rankine cycle (47.6 versus 48.3 percent) and the higher auxiliary power requirement for the sCO_2 plant compared to the Rankine plant at the same net power output.

A systems analysis of a sCO_2 power cycle without thermal integration and operating at the same process conditions shown in Table 1 yields a cycle efficiency of 49.0 percent. The thermal integration with the flue gas heat exchanger used in the baseline sCO_2 recompression plant increases the total fraction of coal thermal input that can be utilized in the power cycle (by 5.9 percent), but decreases the cycle efficiency because it lowers the amount of CO_2 that bypasses the cooler. In the balance, the thermal integration is worthwhile because the increase in recovered heat more than offsets the drop in cycle efficiency.

The increase in the auxiliary power requirement for the baseline sCO_2 plant compared to the reference Rankine plant is primarily due to an increased power requirement for the recycle flue induction fan, due to the pressure drop incurred by the flue gas recuperator.

5 Alternative Cycle Configurations Examined to Improve Performance

Additional analyses were conducted to determine if further improvement in the sCO_2 Brayton cycle performance could be obtained by altering the cycle configuration. Three additional configurations were analyzed for the baseline sCO_2 conceptual commercial power plant. These were:

- Recompression cycle with reheat
- Recompression cycle with main compressor intercooling
- Recompression cycle with combination of reheat and intercooling

These process modifications are intended to either 1) increase the fraction of plant thermal input that is captured in the sCO_2 cycle, 2) increase the sCO_2 power cycle efficiency, 3) decrease the sCO_2 plant auxiliary power requirement, or 4) provide some combination of these three effects.

5.1 Performance Comparison with Reheat sCO_2 Case

Figure 3 shows a BFD of the sCO_2 recompression Brayton power plant with reheat. The new units for this configuration are shown in green. In this configuration the sCO_2 exiting the high pressure (HP) expansion turbine is returned to the CFB furnace to be reheated before it is expanded in the intermediate pressure (IP) turbine. The pressure ratios in the two turbines are approximately equal. All other aspects of the plant configuration are the same as for the baseline sCO_2 recompression power plant.

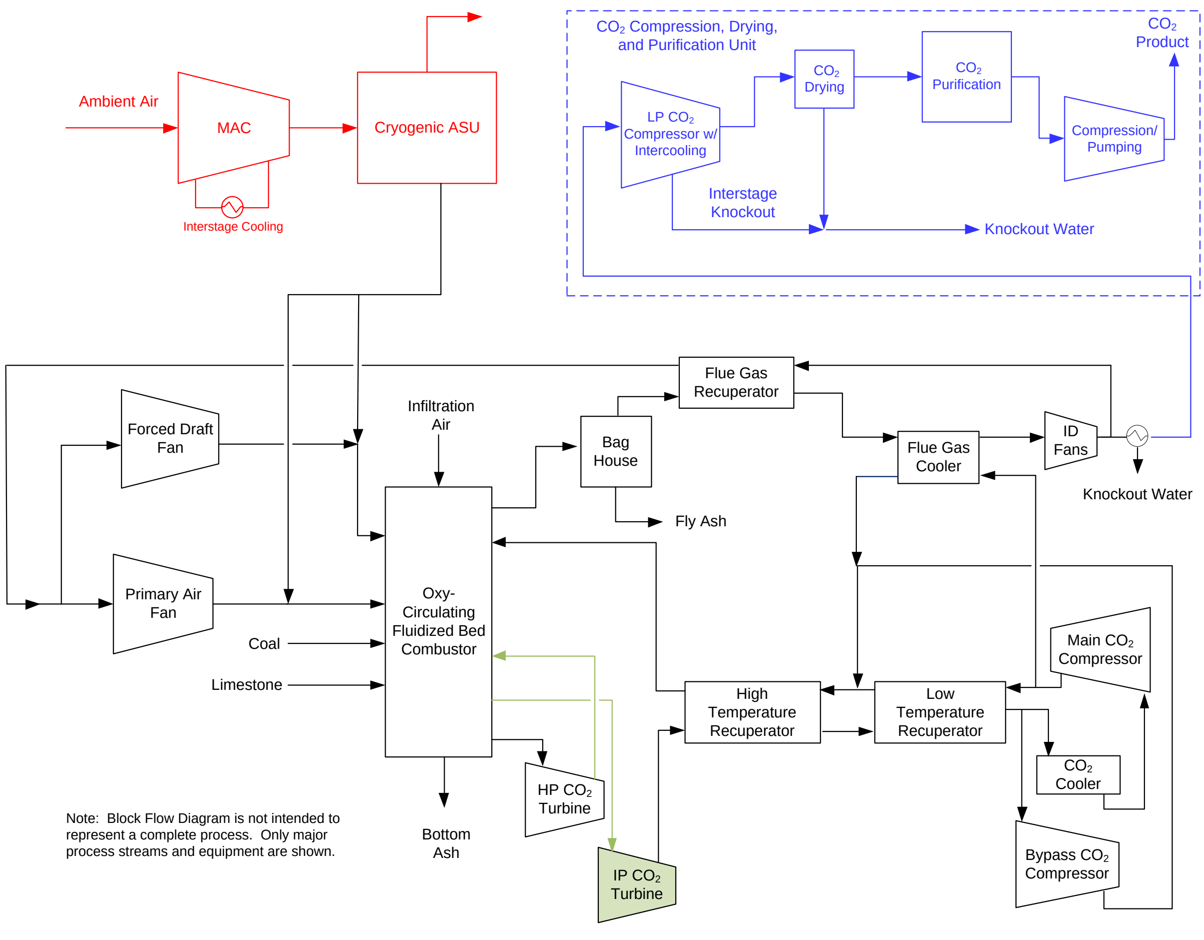

Figure 3 Block flow diagram for the sCO_2 recompression Brayton cycle with reheat

Table 3 compares the performance of the Rankine and the sCO_2 Brayton cycles with and without reheat. Because of reheat, the sCO_2 power cycle efficiency has increased from 47.6 to 49.3 percent, and the overall plant efficiency has increased from 32.9 to 34.4 percent for a 1.5 percentage point increase. The process efficiency for the sCO_2 reheat plant is 1.2 percentage points higher than the reference Rankine plant.

Table 3 Performance comparison between Rankine and recompression sCO_2 Brayton cycles with and without reheat

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	Baseline sCO_2 Brayton Cycle (620 °C, 1148 °F)	sCO_2 Brayton Cycle Reheat (620 °C, 1148 °F)
CFB Coal Flow Rate (lb/hr)	483,994	488,528	467,009
Limestone Flow Rate (lb/hr)	116,535	117,729	112,544
Oxygen Flow Rate (lb/hr)	1,034,064	1,045,070	999,113
sCO_2 Flow Rate (lb/hr)	---	43,395,000	40,185,000
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**34.4**
HHV Heat Rate (Btu/kWh)	10,267	10,363	9,906
sCO_2 Power Cycle Efficiency (%)	---	**47.6**	**49.3**
sCO_2 Cycle Heat Rate (Btu/kWh)	---	7,167	6,929
Steam Power Cycle Efficiency (%)	**48.3**	---	---
Steam Cycle Heat Rate (Btu/kWh)	7,069	---	---
Coal Thermal Input (MMBtu/hr)	5,646	5,699	5,448
Power Cycle Thermal Input (MMBtu/hr)	5,109	5,214	4,985
Fractional Thermal Input to Power Cycle	0.905	0.915	0.915
Raw Water Withdrawal (gpm)	9,127	9,877	9,247
Power Summary (kW)			
Steam Turbine Power Output	722,836	0	0
sCO_2 Turbine Power Output	0	727,460	719,440
Gross Power Output	722,836	727,460	719,440
Total Auxiliary Power Load	172,851	177,464	169,446
Net Power Output	549,985	549,996	549,994

5.2 Performance Comparison with Intercooled sCO_2 Case

Figure 4 shows the BFD for the sCO_2 plant with main compressor intercooling. This BFD is the same as for Figure 2 except for the intercooler between the two main compressor stages. There is no intercooler on the bypass compressor.

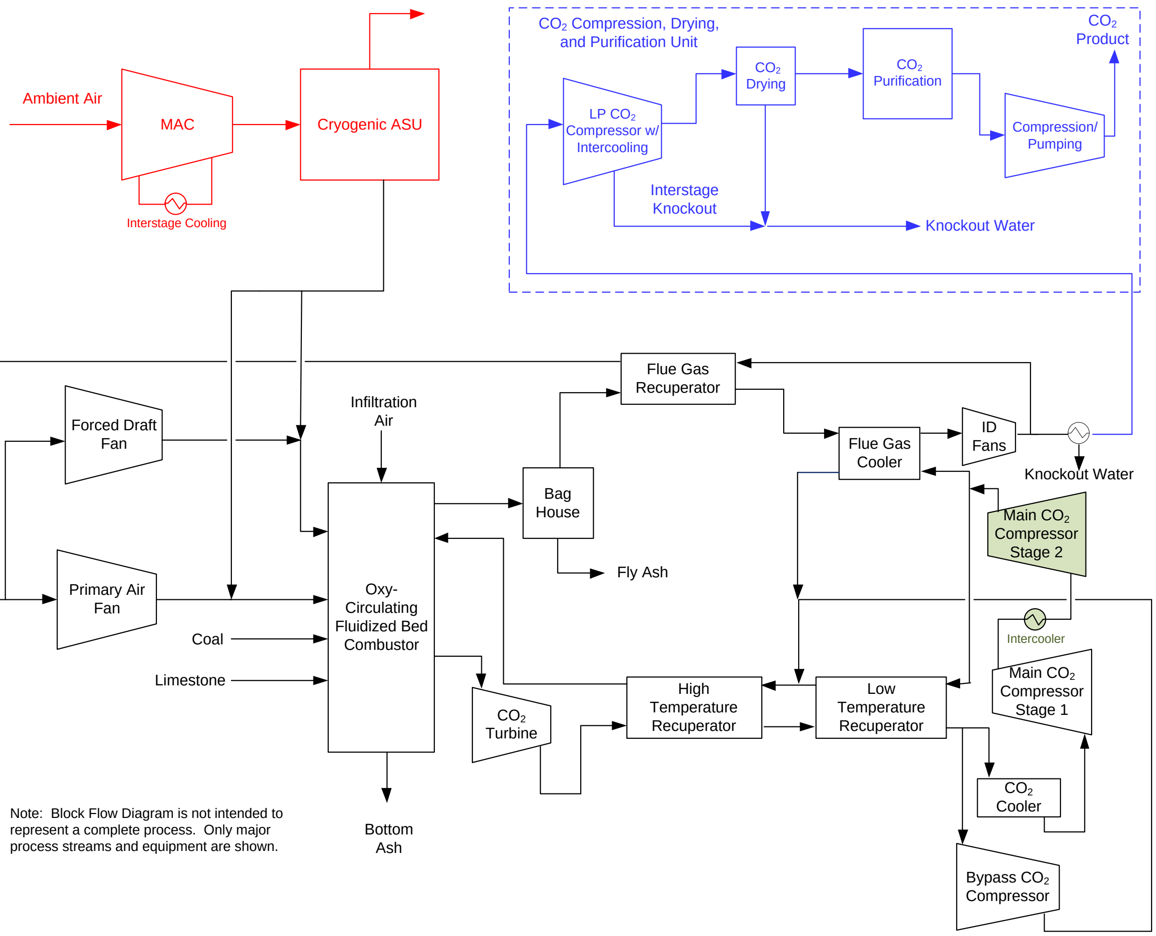

Figure 4 Block flow diagram for the sCO_2 recompression Brayton cycle with main compressor intercooling

Table 4 shows the comparative performance of the Rankine and the baseline sCO_2 Brayton cycles with and without main compressor intercooling. The overall plant HHV efficiency increases from 32.93 to 33.98 percent. This is due to both an increase in the sCO_2 power cycle efficiency from 47.61 to 48.09 percent and an increase in the fraction of coal thermal input recovered in the sCO_2 power cycle, because additional heat enters the sCO_2 cycle from the flue gas exchanger due to the lower cold side entrance temperature.

Table 4 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 sCO_2 Brayton Cycle (620 °C, 1148 °F)**	**sCO_2 Brayton Cycle Intercooler (620 °C, 1148 °F)**
CFB Coal Flow Rate (lb/hr)	483,994	488,528	473,443
Limestone Flow Rate (lb/hr)	116,535	117,729	114,094
Oxygen Flow Rate (lb/hr)	1,034,064	1,045,070	1,012,860
sCO_2 Flow Rate (lb/hr)	---	43,395,000	40,042,800
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**34.0**

Parameter	Rankine Steam Cycle (593°C, 1100 °F)	Baseline sCO_2 Brayton Cycle (620 °C, 1148 °F)	sCO_2 Brayton Cycle Intercooler (620 °C, 1148 °F)
HHV Heat Rate (Btu/kWh)	10,267	10,363	10,042
sCO_2 Power Cycle Efficiency (%)	---	**47.6**	**48.1**
sCO_2 Cycle Heat Rate (Btu/kWh)	---	7,167	7,095
Steam Power Cycle Efficiency (%)	**48.3**	---	---
Steam Cycle Heat Rate (Btu/kWh)	7,069	---	---
Coal Thermal Input (MMBtu/hr)	5,646	5,699	5,523
Power Cycle Thermal Input (MMBtu/hr)	5,109	5,214	5,122
Fractional Thermal Input to Power	0.905	0.915	0.927
Raw Water Withdrawal (gpm)	9,127	9,877	9,443
Power Summary (kW)			
Steam Turbine Power Output	722,836	0	0
sCO_2 Turbine Power Output	0	727,460	721,822
Gross Power Output	722,836	727,460	721,822
Total Auxiliary Power Load	172,851	177,464	171,809
Net Power Output	549,985	549,996	550,013

5.3 Performance Comparison with Reheat and Intercooled sCO_2 Case

Figure 5 shows the BFD for the sCO_2 plant with both reheat and main compressor intercooling. This BFD is slightly more complicated than the simple combination of figures 8 and 9 in that there is a third recuperator stage. In this configuration, the cold side effluent from the HTR is partially heated in the freeboard section of the CFB and then further heated using the effluent from the IP turbine in a very high temperature recuperator (VTR). This heat exchange configuration is not thermodynamically favorable in the sCO_2 cycle with reheat because in that configuration, the HTR cold side effluent temperature is relatively high and a VTR does not offer an advantage. In the sCO_2 cycle with both reheat and compressor intercooling, the HTR cold side effluent temperature is considerably lower and the use of a VTR maximizes the total amount of heat that can be recuperated.

Table 5 shows the performance comparison between the Rankine cycle, the baseline sCO_2 recompression cycle, and the sCO_2 recompression cycle with the combination of reheat and main compressor intercooling. This combination acts synergistically to increase both the power cycle efficiency (from 47.6 to 49.4 percent) and the overall process efficiency (from 32.9 to 35.2 percent). Also, the efficiency benefits gained from using reheat and main compressor intercooling are nearly independent. The increase in overall plant efficiency from using both reheat and intercooling is almost the same as the sum of the increases in process efficiency from using each separately.

Compared to the reference Rankine cycle plant, the sCO_2 cycle plant configured with reheat and main compressor intercooling has a 2.0 percentage point increase in overall process efficiency.

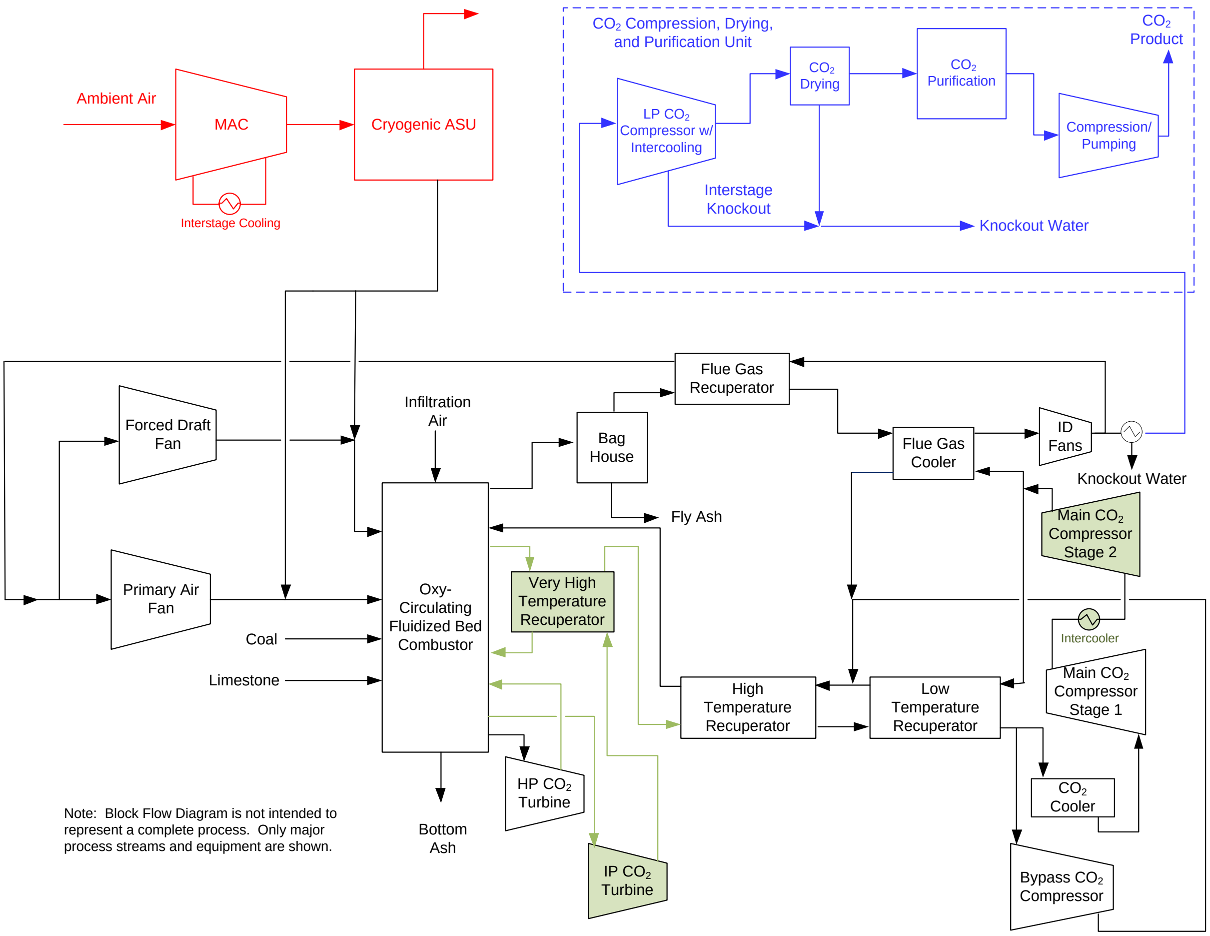

Figure 5 Block flow diagram for the sCO_2 recompression Brayton cycle with reheat and main compressor intercooling

Table 5 Performance comparison between Rankine, baseline recompression cycle, and sCO_2 Brayton cycle with reheat and main compressor intercooling

Parameter	**Rankine Steam Cycle (593 °C, 1100 °F)**	**Baseline sCO_2 Brayton Cycle (620 °C, 1148 °F)**	**sCO_2 Brayton Cycle Reheat and Intercooler (620 °C, 1148 °F)**
CFB Coal Flow Rate (lb/hr)	483,994	488,528	456,867
Limestone Flow Rate (lb/hr)	116,535	117,729	110,099
Oxygen Flow Rate (lb/hr)	1,034,064	1,045,070	977,409
sCO_2 Flow Rate (lb/hr)	---	43,395,000	37,243,400
Net Plant Efficiency (HHV %)	**33.2**	**32.9**	**35.2**
HHV Heat Rate (Btu/kWh)	10,267	10,363	9,691
sCO_2 Power Cycle Efficiency (%)	---	**47.6**	**49.4**

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	Baseline sCO_2 Brayton Cycle (620 °C, 1148 °F)	sCO_2 Brayton Cycle Reheat and Intercooler (620 °C, 1148 °F)
sCO_2 Cycle Heat Rate (Btu/kWh)	---	7,167	6,905
Steam Power Cycle Efficiency (%)	**48.3**	---	---
Steam Cycle Heat Rate (Btu/kWh)	7,069	---	---
Coal Thermal Input (MMBtu/hr)	5,646	5,699	5,330
Power Cycle Thermal Input	5,109	5,214	4,941
Fractional Thermal Input to Power	0.905	0.915	0.927
Raw Water Withdrawal (gpm)	9,127	9,877	8,925
Power Summary (kW)			
Steam Turbine Power Output	722,836	0	0
sCO_2 Turbine Power Output	0	727,460	715,614
Gross Power Output	722,836	727,460	715,614
Total Auxiliary Power Load	172,851	177,464	165,606
Net Power Output	549,985	549,996	550,008

6 Sensitivity Analyses to sCO_2 Cycle Operating Parameters

NETL has conducted multiple studies analyzing the performance of indirect sCO_2 cycles and its dependence on the cycle operating parameters. These analyses have been conducted on both isolated sCO_2 cycles (9) and fully integrated power plants (14). These studies have examined the impact on cycle and system efficiencies of changes to the TIT, the maximum and minimum cycle pressures, the CO_2 cooler temperature, the minimum approach temperature in the recuperators, the cycle pressure drop, and the turbo-machinery efficiencies. Of all the parameters examined, the TIT exerts the strongest impact on cycle efficiency. Prior analyses focused on the sCO_2 cycle indicate that cycle efficiencies can increase on the order of 1 percentage point for every 25 °C increase in the TIT (9).

7 Performance Comparison with Elevated Turbine Inlet Temperature Case

An additional case was evaluated using the sCO_2 recompression plant configuration with both reheat and main CO_2 compressor intercooling but with an elevated TIT of 1400 °F (760 °C). The plant schematic is the same as shown in Figure 5. The operating parameters were the same as shown in Table 1 except for the elevated TIT.

Table 6 shows the performance comparison between the Rankine cycle and the 620 °C and 760 °C sCO_2 cycle plants. The cycle efficiency for the high TIT plant is 4.4 percentage points higher than the cycle efficiency for the low TIT plant (53.8 versus 49.4 percent), which is reasonably close to what the heuristic stated in Section 6 would predict. The process efficiency increases 4.1 percentage points (from 35.2 to 39.3 percent), which is almost the same as for the cycle efficiency.

Parameter	Rankine Steam Cycle (593 °C, 1100 °F)	sCO_2 Brayton Cycle Reheat and Intercooler (760 °C, 1400 °F)	sCO_2 Brayton Cycle Reheat and Intercooler (760 °C, 1400 °F)
CFB Coal Flow Rate (lb/hr)	483,994	456,867	408,951
Limestone Flow Rate (lb/hr)	116,535	110,099	98,552
Oxygen Flow Rate (lb/hr)	1,034,064	977,409	874,833
sCO_2 Flow Rate (lb/hr)	---	37,243,400	29,848,100
Net Plant Efficiency (HHV %)	**33.2**	**35.2**	**39.3**
HHV Heat Rate (Btu/kWh)	10,267	9,691	8,675
sCO_2 Power Cycle Efficiency (%)	---	**49.42**	**53.85**
sCO_2 Cycle Heat Rate (Btu/kWh)	---	6,905	6,337
Steam Power Cycle Efficiency (%)	**48.3**	---	---
Steam Cycle Heat Rate (Btu/kWh)	7,069	---	---
Coal Thermal Input (MMBtu/hr)	5,646	5,330	4,771
Power Cycle Thermal Input (MMBtu/hr)	5,109	4,941	4,421
Fractional Thermal Input to Power Cycle	0.905	0.927	0.927
Raw Water Withdrawal (gpm)	9,127	8,925	7,472
Power Summary (kW)			
Steam Turbine Power Output	722,836	0	0
sCO_2 Turbine Power Output	0	715,614	697,710
Gross Power Output	722,836	715,614	697,710
Total Auxiliary Power Load	**172,851**	**165,606**	**147,714**
Net Power Output	549,985	550,008	549,996

8 Summary and Conclusions

This paper has investigated the performance of a power plant based on the sCO_2 recompression Brayton cycle indirectly heated by a coal oxy-fired atmospheric CFB boiler and compared it to a reference oxy-fired CFB supercritical steam Rankine cycle power plant. All the power plants analyzed used a single power cycle (i.e., no combined cycle configurations were considered) and were of equal net output of 550 MW, and designed to capture over 95 percent of the CO_2. The performance estimates for the power plants were based on steady state simulations using Aspen models having comparable accuracy and computational basis.

Four configurations for the sCO_2 recompression cycle were analyzed. The first configuration was a baseline sCO_2 plant that used a simple recompression cycle configuration and was thermally integrated with the plant via the CFB and a flue gas heat exchanger. The nominal operating state point for this plant was based on a prior study that undertook a detailed thermodynamic analysis of an isolated sCO_2 power cycle with a generic heat source. The TIT for the baseline case was 1148 °F (620 °C), which is comparable to the conditions used in the supercritical Rankine cycle. The results indicated that the reference Rankine plant and the baseline sCO_2 Brayton plant have very similar performance with the Rankine plant, having a modestly higher (0.3 percentage points) process efficiency.

Also analyzed were plants with alternative sCO_2 cycle configurations expected to yield higher process efficiencies than the baseline sCO_2 plant. These included a sCO_2 configuration with reheat, a configuration with main CO_2 compressor intercooling, and a configuration with both reheat and intercooling. The latter configuration was also analyzed at an elevated TIT of 1400 °F (760 °C). The overall HHV plant efficiencies for all of the cases analyzed are shown in Figure 6.

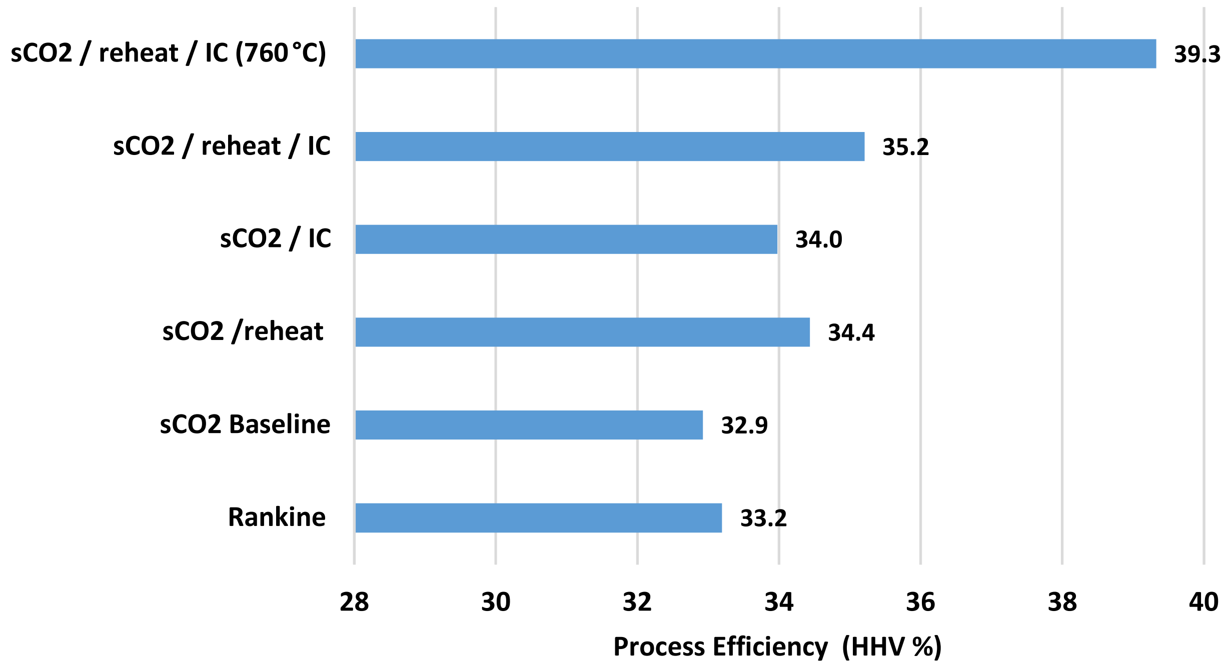

Figure 6 Summary of plant efficiencies

All of the sCO_2 plants with more advanced configurations than the baseline had a higher process efficiency than the reference Rankine plant. The configuration modifications led to a higher process efficiency due to multiple factors. The use of reheat, main CO_2 compressor intercooling, and a combination of reheat and main CO_2 compressor intercooling all led to significant increases in the power cycle efficiency. When reheat and intercooling were used together, the increase in power cycle efficiency was almost equal to the sum of the increases observed from using reheat and intercooling singly.

A second factor leading to increases in power plant efficiency for the configurations that used intercooling was a slight increase in the fraction of process thermal input that was recovered in the power cycle. This occurred because the flue gas heat exchangers could extract more heat from the flue gas due to the lower cold side entrance temperature.

A third factor leading to increases in power plant efficiency that occurred for all the advanced configurations was a very slight drop in the relative parasitic power for the plant. This is a secondary effect resulting from the increased process efficiency whereby less parasitic power is needed for the cooling water pumps and the cooling tower fan. The drop in relative parasitic power was approximately 0.1 percent for the reheat sCO_2 plant, 0.1 percent for the sCO_2 plant with intercooling, 0.2 percent for the sCO_2 plant with both reheat and intercooling with a TIT of 620 °C, and 0.6 percent for the sCO_2 plant with both reheat and intercooling with a TIT of 760 °C.

The sCO_2 recompression cycle power plant that used reheat and main CO_2 compressor intercooling with a TIT of 620 °C is the configuration most comparable to the reference Rankine cycle. Both plants use similar TIT and both employ reheat. The systems analysis results showed that this sCO_2 plant attained a 2.0 percentage point higher efficiency than the reference Rankine cycle. This result is on the low end of the efficiency difference range reported in other studies (2 – 6 percentage points) but even with the configuration enhancements, this sCO_2 plant configuration is not fully optimized for performance. Further, the TIT of 620 °C is on the low range of TIT for which the sCO_2 recompression cycle is expected to offer greater performance than a comparable Rankine cycle. NETL is currently undertaking a systems analysis of a Rankine plant based on an advanced ultra-supercritical steam cycle with conditions comparable to the sCO_2 plant having a TIT of 760 °C. The results of that study will help determine if indirect-fired sCO_2 power plants have a greater performance advantage over comparable Rankine plants at elevated TIT.

The next planned phase of this work will augment the performance analysis with an economic analysis of the sCO_2 power plants.

NOMENCLATURE

Aspen	=	Aspen Plus®
ASU	=	Air separation unit
atm	=	Atmosphere (14.696 psi)
BFD	=	Block flow diagram
Btu	=	British thermal unit
Btu/hr	=	British thermal units per hour
Btu/kWh	=	British thermal units per kilowatt hour
CCCMP	=	Clean Coal and Carbon Management Program
CCS	=	Carbon capture and storage
CFB	=	Circulating fluid bed
CO_2	=	Carbon dioxide
CPU	=	CO_2 purification unit
DOE	=	Department of Energy
EERE	=	Energy Efficiency and Renewable Energy
EOR	=	Enhanced oil recovery
FE	=	Fossil energy
FG	=	Flue gas
gpm	=	Gallons per minute
h, hr	=	Hour
H_2O	=	Water
HHV	=	Higher heating value
HP	=	High pressure
HTR	=	High temperature recuperator
IC	=	Intercooler
ID	=	Induced draft
IP	=	Intermediate pressure
ISO	=	International Organization for Standardization
kW	=	Kilowatt
lb	=	Pound
lb/hr	=	Pounds per hour
lbmol	=	Pound mole
lbmole	=	Pound mole
LP	=	Low pressure
LTR	=	Low temperature recuperator
MAC	=	Main air compressor
MM	=	Million
MMBtu	=	Million British thermal units
MPa	=	Mega Pascal
MW	=	Megawatt
MWh	=	Megawatt-hour
N_2	=	Nitrogen
NE	=	Nuclear energy
NETL	=	National Energy Technology Laboratory
O_2	=	Oxygen
ppmv	=	Parts per million volume

PR	=	Pressure ratio	T	=	Temperature
psi	=	Pound per square inch	TIT	=	Turbine inlet temperature
psia	=	Pound per square inch absolute	TRL	=	Technical readiness level
psig	=	Pound per square inch gauge	U.S.	=	United States
R&D	=	Research and development	VTR	=	Very high temperature recuperator
RD&D	=	Research, development, and demonstration	°C	=	Degrees Celsius
SC	=	Supercritical	°F	=	Degrees Fahrenheit
sCO_2	=	Supercritical carbon dioxide			

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