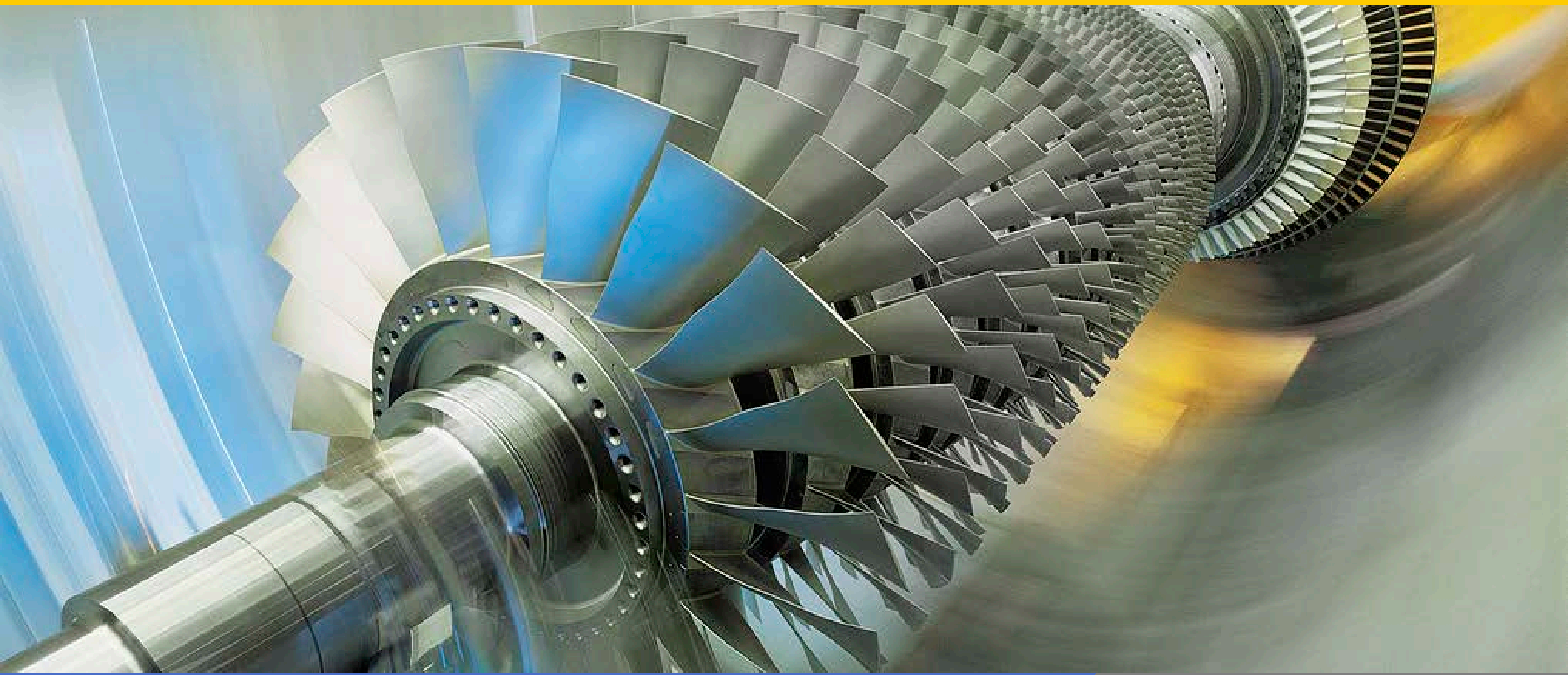
Driving Innovation ♦ Delivering Results



Design of a Commercial Scale Oxy-Coal Supercritical CO_2 Power Cycle
DOE/NETL-2015/1733

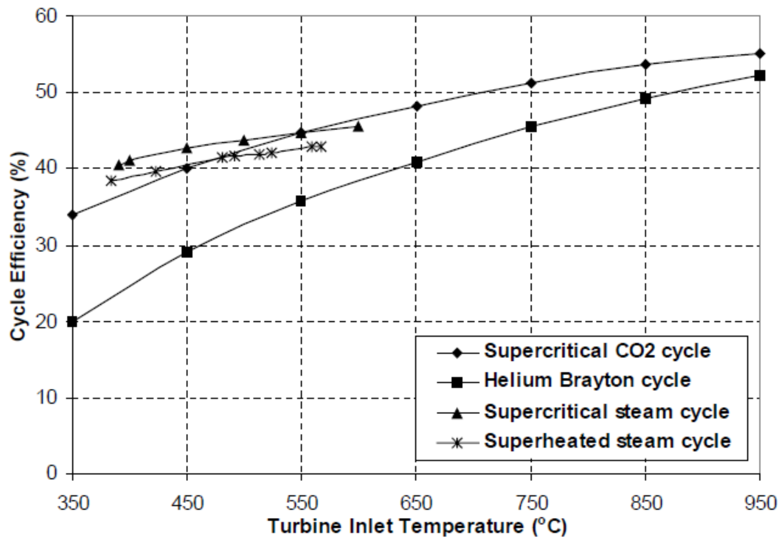
Nathan Weiland, Wally Shelton (NETL), Chuck White (Noblis)

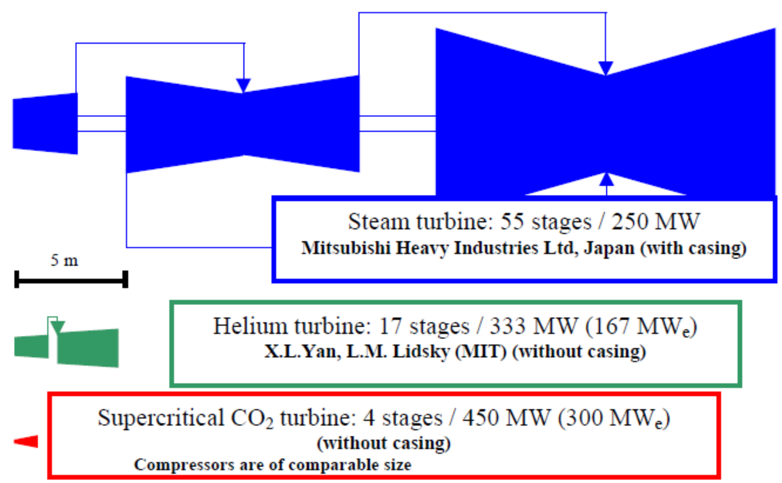
October 7, 2015

2015 Pittsburgh Coal Conference

Why Use Supercritical CO_2 (sCO_2) for Power Cycles?

- **Potential higher efficiency relative to traditional fossil energy cycles**
  - Recuperation of high-quality heat from the turbine exhaust
  - sCO_2 has beneficial thermodynamic properties (high density and specific heat) near the critical point
- **Reduced turbomachinery equipment sizes due to higher working fluid density results in reduced capital costs**
- **sCO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O**



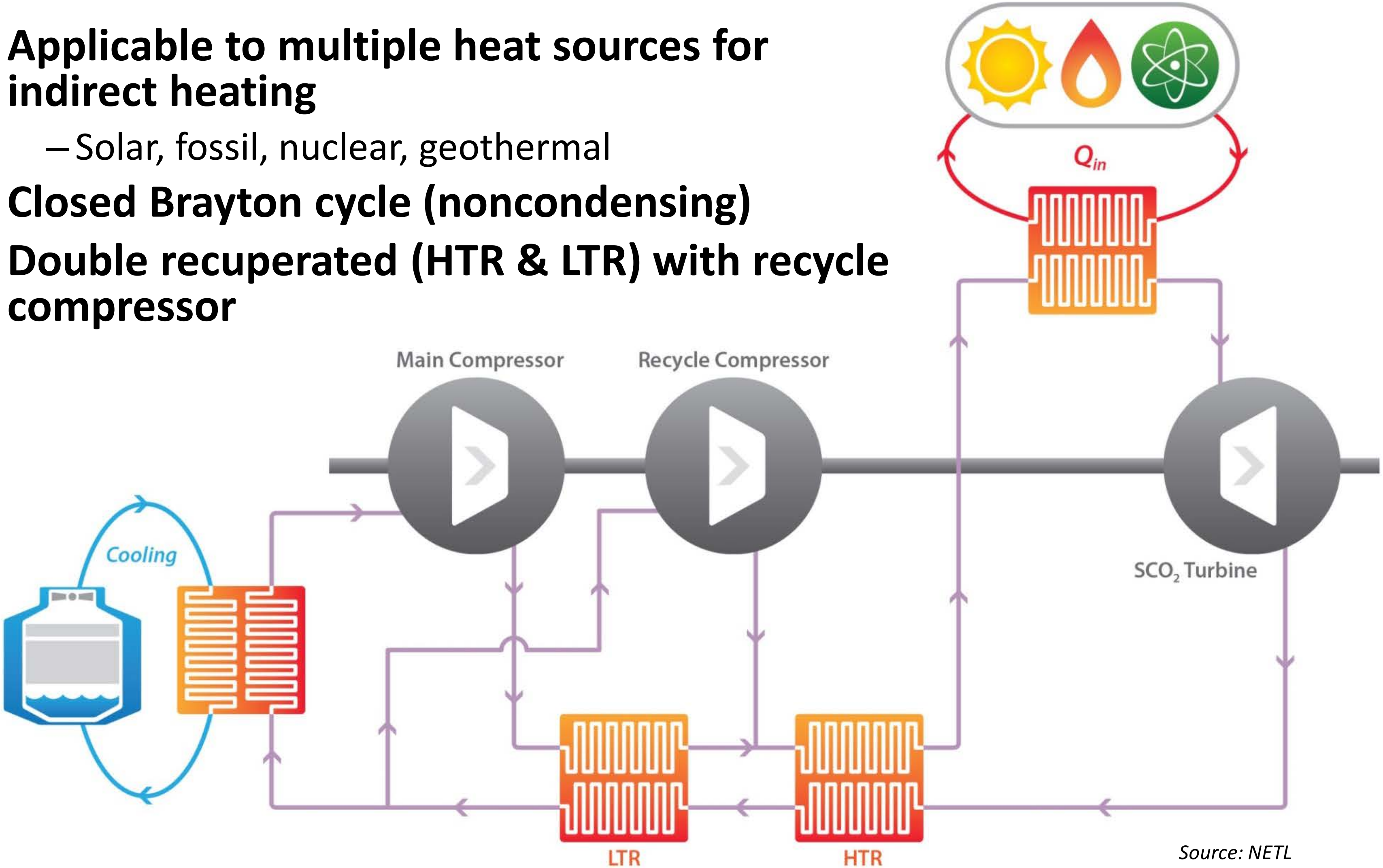


Source: Dostal, 2004[1]

[1] *V. Dostal, M.J. Driscoll, and P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Report MIT-ANP-TR-100, March 2004.*

sCO_2 Recompression Brayton Cycle

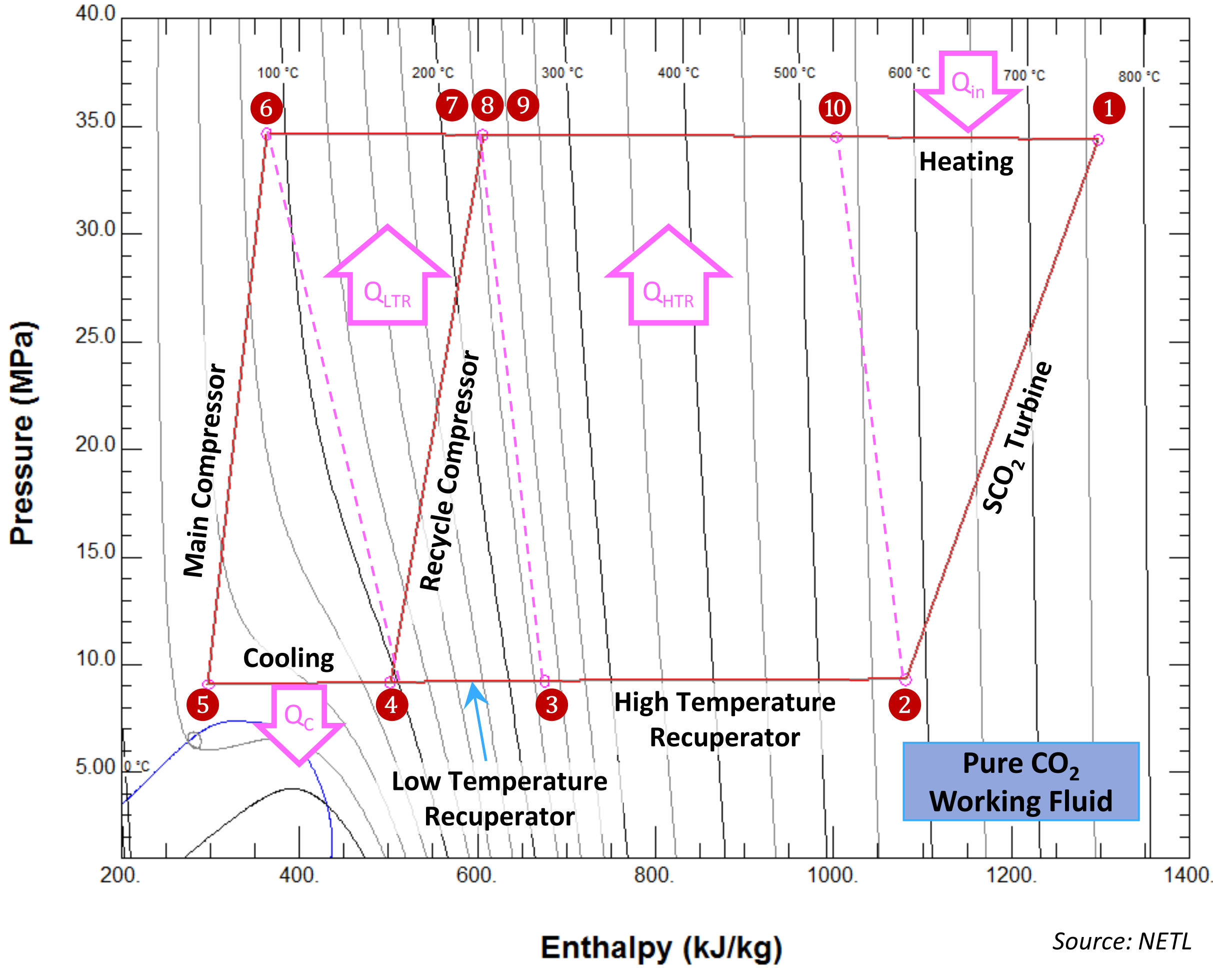
- **Applicable to multiple heat sources for indirect heating**
  - Solar, fossil, nuclear, geothermal
- **Closed Brayton cycle (noncondensing)**
- **Double recuperated (HTR & LTR) with recycle compressor**



Source: NETL

Integration of sCO_2 Recompression Cycles

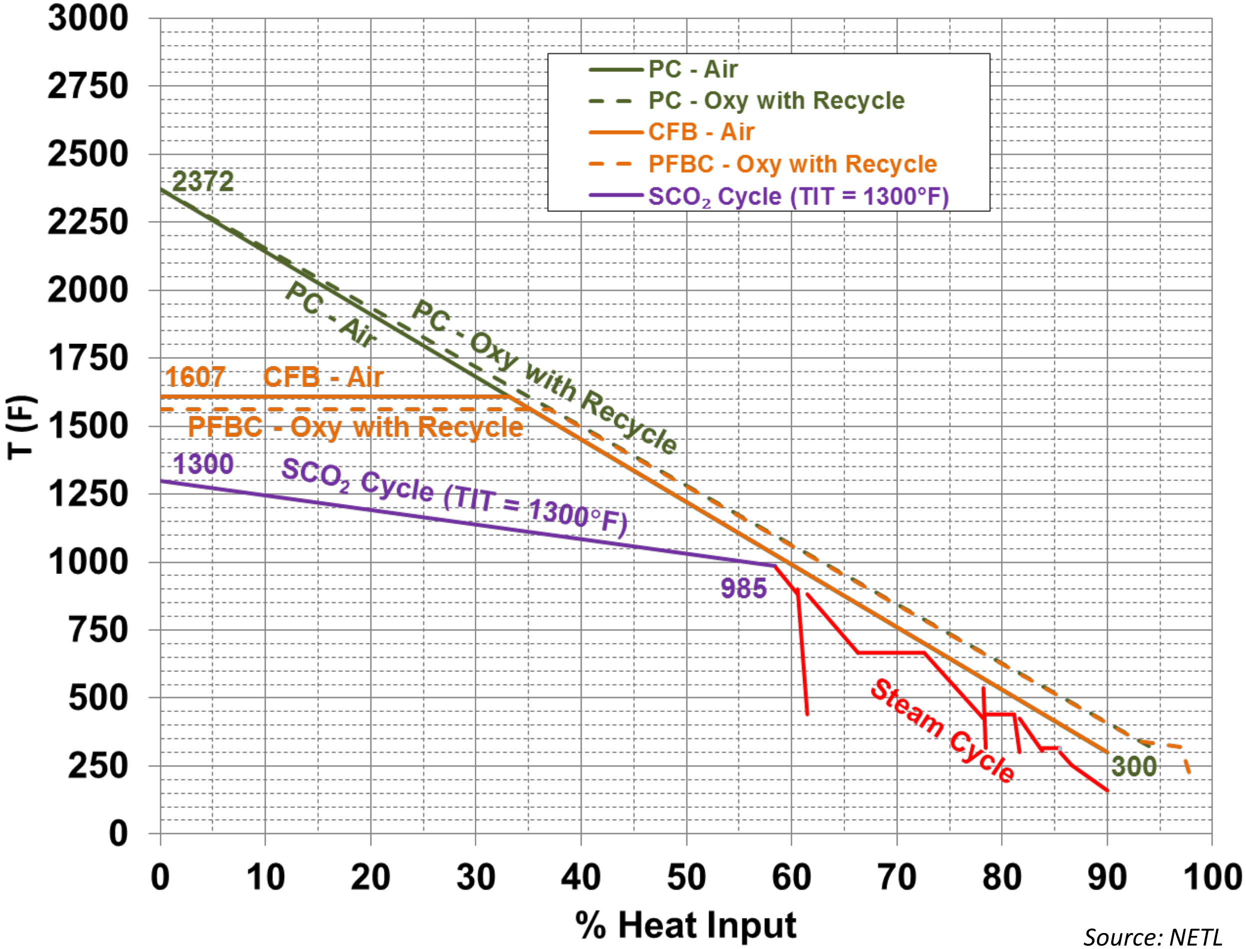
- **High cycle efficiency due to recuperation and high average temperature of heat addition**
- **Ideal for constant temperature heat sources:**
  - Concentrated Solar
  - Nuclear
- **More difficult to integrate with variable temperature, fossil-fueled heat sources**



Source: NETL

NETL Heat Source Integration Study

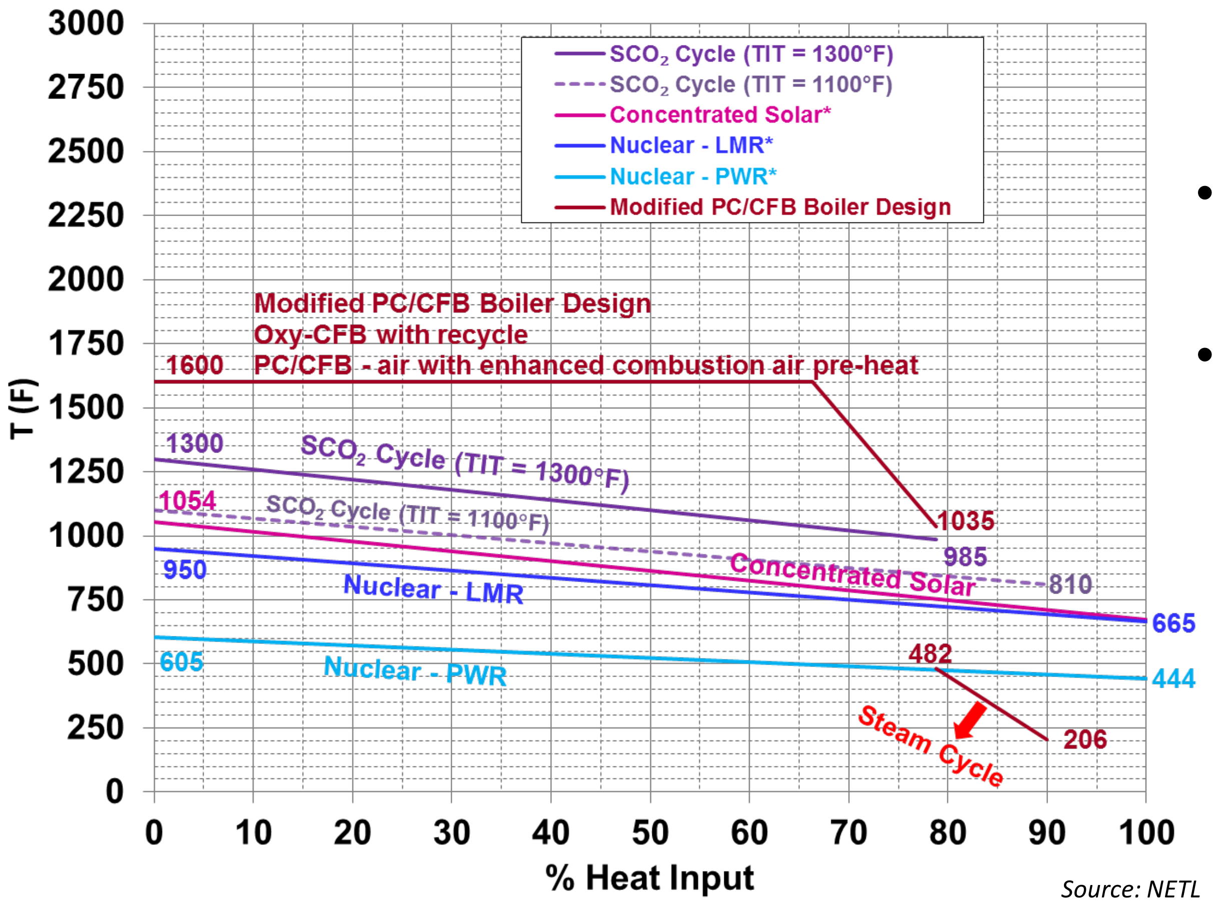
T-Q Diagram for Conventional Coal-Based Systems and example indirect sCO_2 cycle



Source: NETL

- **Fossil-fueled heat sources provide large slope of T versus Q**
  - Conventional PC, CFB, and oxy-combustion boilers
- **Steam Rankine cycles are tuned to most economically convert this heat source temperature profile to power**
- **Pairing these heat sources and sCO_2 power cycle still requires a steam bottoming cycle**

Matching Heat Sources and Power Cycles

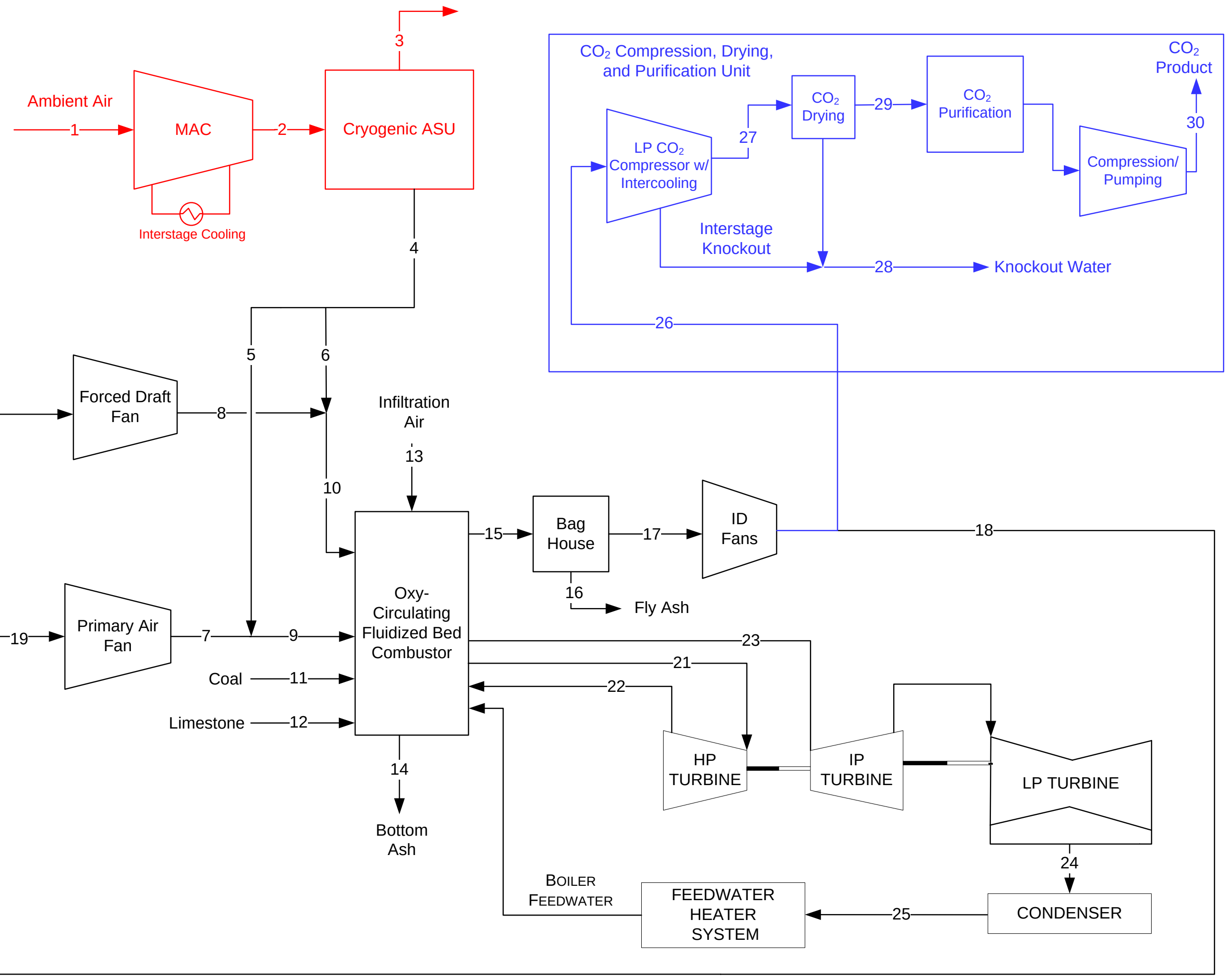


Source: NETL

- sCO_2 cycles well suited to T-Q heat source profiles of concentrated solar and nuclear systems
- Fossil-fueled sources need to recover low grade heat
- Enhanced preheating for combustion air or CO_2 recycle
  - Applicable to PFBC, CFB, and conventional PC boilers
  - Air- or oxy-fired
  - Tailors the T-Q profile to match sCO_2 cycle requirements
  - Minimizes the bottoming cycle

Reference Cycle B22F: Oxy-CFB Boiler

- **Case B22F[2]: Oxy-Circulating Fluidized Bed (CFB) Boiler with bituminous coal**
- **550 MWe plant capacity**
- **Major subsystems:**
  - Oxy-CFB combustor
  - Supercritical steam cycle*
  - Cryogenic air separation unit (ASU)*
  - Auto-refrigerated CO_2 compression, drying, and purification unit (CPU)*



Source: NETL

*Utilize performance/cost from Advanced Atmospheric Oxy-Combustion Study[3]

[2]NETL – Techno-economics of Bituminous Coal Atmospheric Air and Oxy-combustion Plants with Circulating Fluidized Bed Technology. TBD.
[3]NETL – Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants, DOE/NETL- 341/042015, TBD.

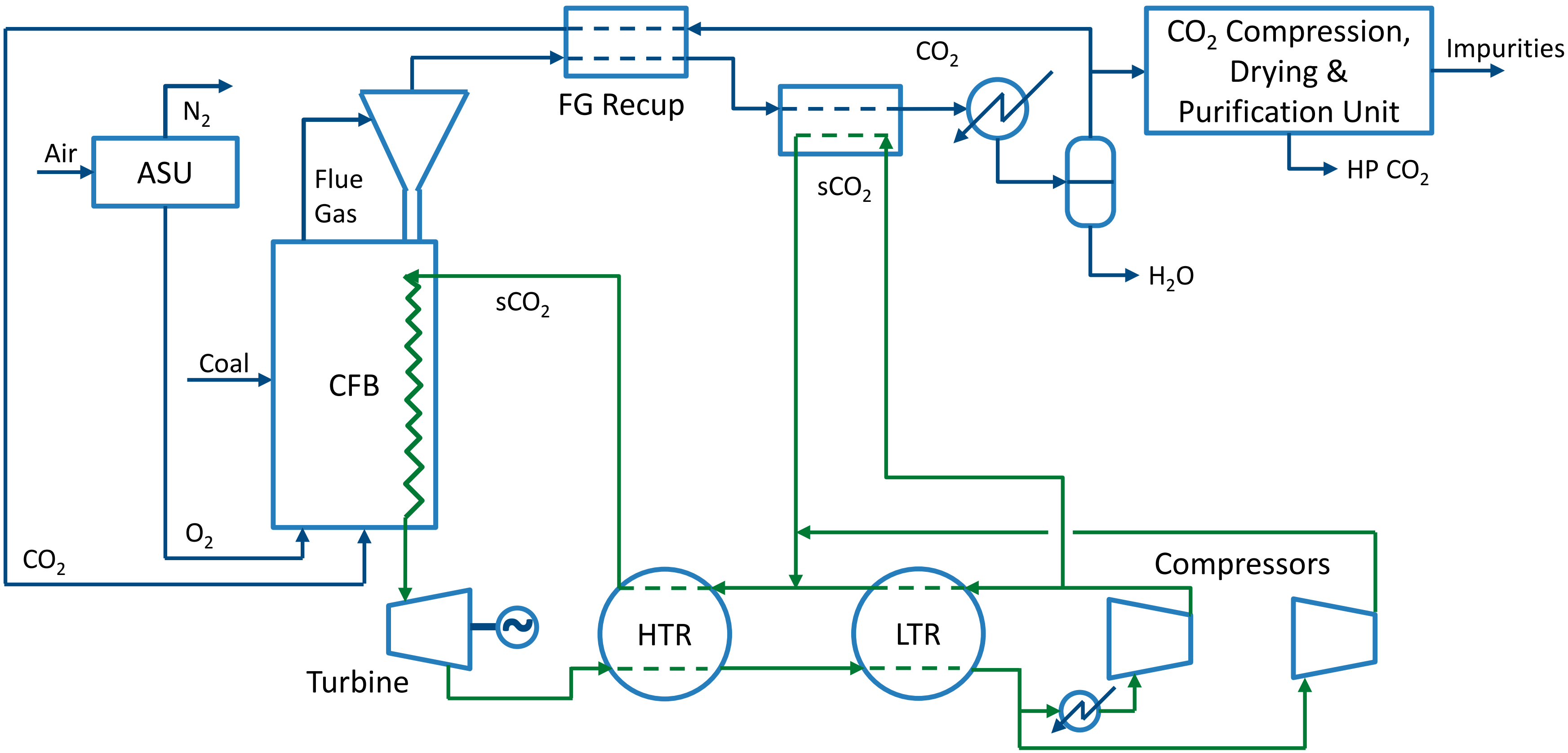
Oxy-CFB Case B22F[2]
Model Description

- **Boiler based on Low Rank CFB boiler configuration**
  – Specified reactions for carbon and sulfur
  – Flue gas recycle set to 45% of total flue gas
  – Solids recycle iterated to achieve >1,600 °F boiler exit temperature
    - Steam cycle heat exchanger following boiler cools to 1,600 °F
  – Total carbon conversion of 99.0%
  – CFB solids recycle is 99.05% - reflects Low Rank CFB boilers
- **In-bed limestone injection for SO_2 capture using 2.4 Ca/S ratio**
  – Single-pass capture of SO_2 is 94%, total SO_2 capture approaches 97%
  – SO_2 emissions meet 1.0 lb/MWh-gross limit
- **NOx emissions meet the MATS 0.7 lb/MWh-gross limit[4]**
- **Mercury emissions meet the MATS $3.0\text{x}10^{-6}$ lb/MWh-gross limit[4]**

[2]NETL – Techno-economics of Bituminous Coal Atmospheric Air and Oxy-combustion Plants with Circulating Fluidized Bed Technology. TBD.
[4]NETL - Assessment of MATS and Coal Combustion Residuals (Proposed Rule/Revised Rule) Impact on Baseline/Pathway Cases: Final Report. May 2014.

Baseline Oxy-fired CFB with Recompression sCO_2 Brayton Cycle

- **ASU, CPU, and Oxy-CFB remain the same**
- **Rankine steam cycle replaced with sCO_2 recompression cycle**
- **CFB Flue Gas preheats CO_2 recycle to CFB and heats sCO_2**
- **sCO_2 main and bypass compressors are driven by the sCO_2 turbine**



Relevant Study Process Parameters

- **Analysis assumes that a viable oxy-CFB redesign for sCO_2 can be attained**
- **Most plant process parameters are identical between the steam oxy-CFB Case B22F[2] and the sCO_2 oxy-CFB cases, including:**
  - Coal type (Illinois #6) and carbon conversion (>99%)
  - CFB operating temperature (1600 °F) and fluidizing gas (O_2/Flue Gas mix)
  - Sulfur, mercury, and CO_2 emissions controls
  - ASU and CPU operating parameters
- **All sCO_2 cycle analyses differ from the reference steam case in:**
  - Coal thermal input of 1416 MWth
  - Flue gas recycle rate of 71.5%, vs. 45% for B22F
  - Explicit thermal integration of the sCO_2 cycle with flue gas
- **Additional sCO_2 cases use same conditions sCO_2 base Case 1**
  - Case 2: Increased sCO_2 T & P, similar to Advanced Ultra-Supercritical (AUSC) conditions for steam Rankine cycles
  - Case 3: Additional Flue Gas heat recovery
  - Case 4: ASU intercooling heat recovery

[2]NETL – Techno-economics of Bituminous Coal Atmospheric Air and Oxy-combustion Plants with Circulating Fluidized Bed Technology. TBD.

Recompression Brayton Cycle

Parameters for Baseline Cycles

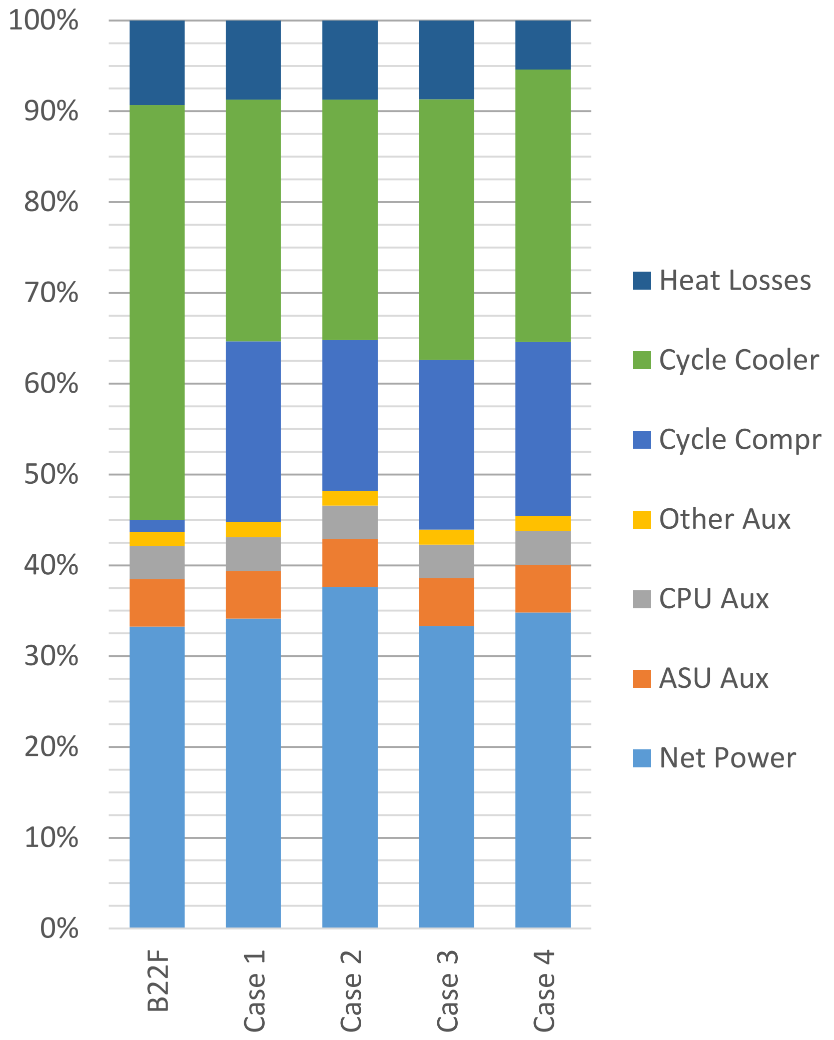
Parameter	Case 1	Case 2	Case 3	Case 4
Max cycle pressure (psia)	3,030	5015	3,030	3,030
Min cycle pressure (psia)	1,150	1,350	1,150	1,150
Pressure ratio	2.63	3.71	2.63	2.63
Turbine inlet temperature (°F)	1,292	1,400	1,292	1,292
Turbine isentropic efficiency	0.927	0.927	0.927	0.927
Compressor isentropic efficiency	0.85	0.85	0.85	0.85
Cycle pressure drop (psia)	60	60	60	60
Minimum temperature approach (°F)	10	10	10	10
CO_2 cooler temperature (°F)	95	95	95	95
Thermal Integration	None	None	Flue Gas+	ASU

Performance of Baseline Cycles

Parameter	B22F	Case 1	Case 2	Case 3	Case 4
Max cycle pressure (psia)	3,500	3,030	5,015	3,030	3,030
Turbine inlet temperature (°F)	1,110	1,292	1,400	1,292	1,292
Additional Thermal Integration	None	None	None	Flue Gas+	ASU
Gross Power Output (MWe)	723	633.3	682.3	622.0	642.9
Plant Auxiliary Power (MWe)	173	150.3	149.9	150.4	150.4
Net Power Output (MWe)	550	482.9	532.4	471.6	492.5
Plant HHV Thermal Efficiency (%)	33.2	34.1	37.6	33.3	34.8
Thermal Input to Cycle (MWth)	1654.8	1292.1	1292.1	1292.5	1338.8
Cycle Thermal Efficiency (%)	48.3	49.0	52.8	48.1	48.0
Cycle Mass Flow (lb/s)	1,224	13,012	9,107	12,602	13,001
Cycle Specific Power (kW_{gross}/[lb/s])	590.9	48.7	74.9	49.4	49.4
Bypass Compressor Flow (%)	--	21.8%	21.7%	18.0%	17.5%
CO_2 Recycle Preheater Duty (%)	0	11.7%	11.7%	9.0%	11.7%
CO_2 Preheat Temperature (°F)	112	980	980	800	980

Baseline Performance Results

- **All sCO_2 cases have higher plant thermal efficiency than the reference steam cycle, B22F**
  - Condenser duty reduced, but compression power increased
- **Case 2: At higher T & P conditions, plant efficiency improves +3.5% points**
  - Due to higher TIT & pressure ratio
- **Case 3: Increased thermal integration with Flue Gas *reduces* plant efficiency -0.8% points**
  - CO_2 recycle preheating is a more effective use of flue gas thermal energy
- **Case 4: ASU thermal integration improves plant efficiency +0.7% points**
  - Recovery of low-grade heat from ASU main air compressor intercooler
  - Similar heat recovery possible with CPU compressor



Recompression Brayton Cycle
Parameters for Sensitivity Studies

Parameter	Case 4'	Case 4a	Case 4b	Case 4c	Case 4d	Case 4e
Max cycle pressure (psia)	3,030	5015	3,030	3,030	3,030	3,030
Min cycle pressure (psia)	1,150	1,350	1,150	1,150	1,150	1,150
Pressure ratio	2.63	3.71	2.63	2.63	2.63	2.63
Turbine inlet temperature (°F)	1,300	1,300	1,382	1,300	1,300	1,300
Turbine isentropic efficiency	0.927	0.927	0.927	0.927	0.927	0.927
Compressor isentropic efficiency	0.85	0.85	0.85	0.80	0.85	0.85
Cycle pressure drop (psia)	60	60	60	60	60	60
Min temperature approach (°F)	10	10	10	10	30	10
CO_2 cooler temperature (°F)	95	95	95	95	95	100
Thermal Integration	ASU	ASU	ASU	ASU	ASU	ASU

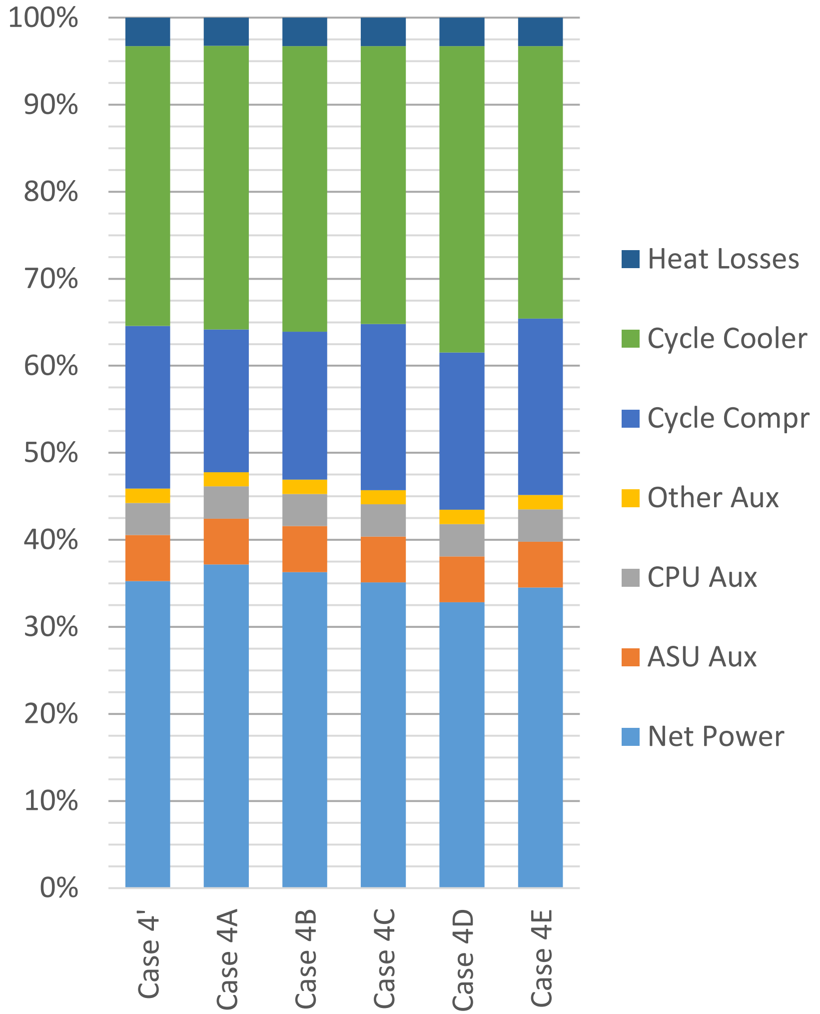
- **Sensitivity studies all performed on an early model (Case 4') with 40% more ASU heat recovery**
  - Sensitivity trends remain the same

Sensitivity Study Performance Results

Parameter	Case 4’	Case 4a	Case 4b	Case 4c	Case 4d	Case 4e
Max cycle pressure (psia)	3,030	5015	3,030	3,030	3,030	3,030
Turbine inlet temperature (°F)	1,300	1,300	1,382	1,300	1,300	1,300
Bypass compressor efficiency	0.85	0.85	0.85	0.80	0.85	0.85
Min temperature approach (°F)	10	10	10	10	30	10
CO_2 cooler temperature (°F)	95	95	95	95	95	100
Gross Power Output (MWe)	649.7	676.3	664.1	647.3	615.3	638.9
Plant Auxiliary Power (MWe)	150.3	150.1	150.2	150.4	150.6	150.4
Net Power Output (MWe)	499.4	526.2	513.9	496.9	464.7	488.5
Plant HHV Thermal Efficiency (%)	35.3	37.2	36.3	35.1	32.8	34.5
Thermal Input to Cycle (MWth)	1369.5	1369.6	1369.0	1369.4	1369.4	1369.4
Cycle Thermal Efficiency (%)	47.4	49.4	48.5	47.3	44.9	46.7
Cycle Mass Flow (lb/s)	13,001	9,489	12,220	13,045	12,383	13,164
Cycle Specific Power (kW_{gross}/[lb/s])	50.0	71.3	54.3	49.6	49.7	48.5
Bypass Compressor Flow (%)	14.6%	15.0%	11.1%	14.7%	14.6%	11.9%

Sensitivity Study Performance Results

- **Case 4A: Higher turbine pressure ratio improves efficiency ~2% points**
  - Due to reduced compression power
- **Case 4B: Higher turbine inlet temperature improves efficiency ~1% point**
  - Due to reduced compression power
- **Case 4C: Minimal plant efficiency change for compressor efficiency reduction**
  - Recovered as preheated sCO_2
- **Case 4D: Higher recuperator approach temperature decreases efficiency 2.5% points**
  - Due to more heat rejection to cooler
- **Case 4E: Higher cooler temperature (5°F) decreases efficiency 0.8% points**



Capital Cost Factors

- **sCO_2 compressors are a large expense relative to feedwater pumps for steam Rankine cycles**
- **Turbine costs for sCO_2 are 50-75% of steam turbine costs*[5,6]***
- **Recuperator costs are higher relative to steam boiler feedwater heaters**
- **sCO_2 piping costs are high relative to steam**
  - Due to much higher mass flows (~10x steam)
    - Reduced by seeking sCO_2 cycle improvements that increase specific power
  - Boiler to Turbine header much more expensive if temperatures require nickel alloys
  - Minimize piping length from boiler to turbine
    - Redesign CFB boiler for turbine-level headers

[5]Le Moullec, Y, "Conceptual study of a high efficiency coal-fired power plant with CO2 capture using a supercritical CO2 Brayton cycle", Energy, 49:32-46, 2013.
*[6]Cheang, V.T., Hedderwick, R.A., and McGregor, C., "Benchmarking supercritical carbon dioxide cycles against steam Rankine cycles for Concentrated Solar Power," Solar Energy, **113**:199–211, (2015).*

Opportunities for Improved sCO_2 Plant Performance and Cost

- **Main sCO_2 compressor intercooling**
  - Increases sCO_2 cycle specific power (MW/flow) to reduce sCO_2 piping cost and overall power block size
  - Reduces compression auxiliary power
- **Condensing CO_2 cycles**
  - Reduces compression auxiliary power
  - Limited by available cooling source temperature
- **Adding reheat to the cycle**
  - Improves specific power (~6%) and cycle efficiency (~1.5% pts.)
  - Increases Boiler to Turbine header piping costs

Conclusions

- **Efficient integration of a recompression sCO_2 power cycle with a coal-fired heat source is possible with a CFB boiler modified with enhanced CO_2 recycle preheating**
  – Matches the boiler T-Q profile to the high temperature heat source requirements of the recompression sCO_2 cycle
  – Plant efficiency improves by ~1% point with baseline sCO_2 cycle
- **Additional sCO_2 cycle efficiency improvements over a steam Rankine cycle oxy-CFB boiler are possible with:**
  – Higher temperature & pressure sCO_2 cycle operation (+4.4% points)
  – Thermal integration of the sCO_2 cycle with the ASU (+1.6% points)
- **Future Work**
  – Analyze impact of sCO_2 power cycles on COE
    - sCO_2 has higher compression, piping, and recuperation costs, lower turbine cost relative to steam
  – Improve sCO_2 cycle efficiency and COE with sCO_2 compressor intercooling, reheating, and/or condensation of sCO_2

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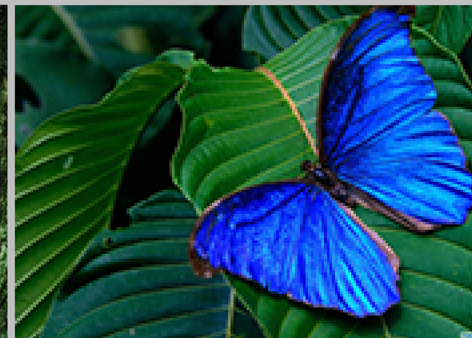
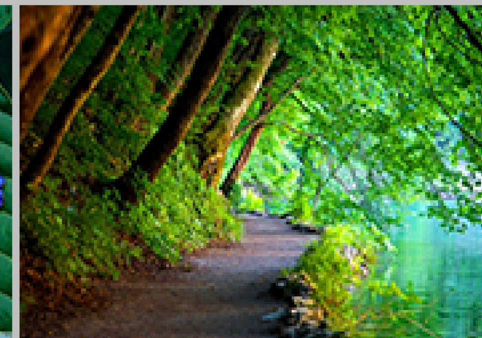

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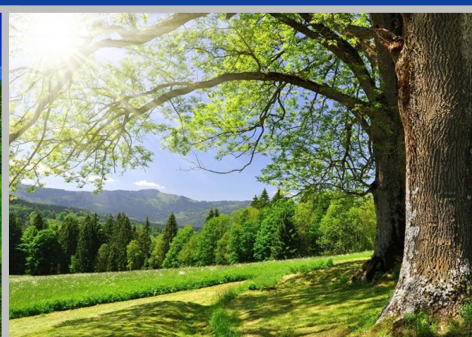
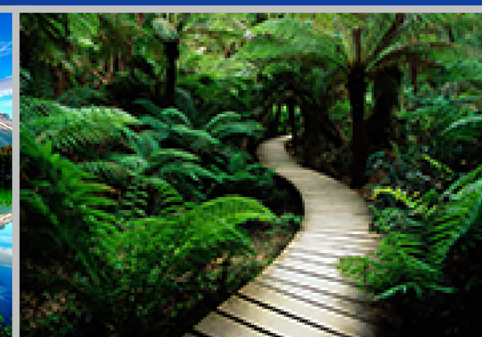




Backup Slides

Site Characteristics and Design Coal

- **Site characteristics and design coal – same as in the Atmospheric Oxy-combustion Study[1]**
  - 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	
Coal seam nomenclature	Herrin (No. 6)	
Coal name	Illinois No. 6	
Mine	Old Ben No. 26	
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**	**Dry**
HHV* (Btu/lb)	11,666	13,126
LHV**(Btu/lb)	11,252	12,660
HHV (kJ/kg)	27,135	30,531
LHV (kJ/kg)	26,171	29,447

[1] *NETL – Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants, DOE/NETL- 341/110813. November 2013.*

Background

Atmospheric Oxy-Combustion

- **Atmospheric oxy-combustion based coal plants were investigated in the NETL advanced oxy-combustion study[1]**
  - Utilized pulverized coal boiler technology
  - Featured a steam Rankine power cycle
  - Employed a CO_2 purification unit to purify the product CO_2 stream to pipeline specifications
- **In addition to the SOA base case, the effect of specific technology advances on the COE and performance of the plant were analyzed:**
  - Advanced membrane O_2 production
  - Advanced cryogenic ASU
  - AUSC steam cycle
  - Advanced flue gas recycle
  - Innovative CO_2 compression concepts
  - Advanced PC boiler design
- **Based on the technology used for O_2 production, two pathway end cases that included the advances cumulatively were also evaluated**

[1] *NETL – Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants, DOE/NETL- 341/110813. November 2013.*

Atmospheric Oxy-CFB Study

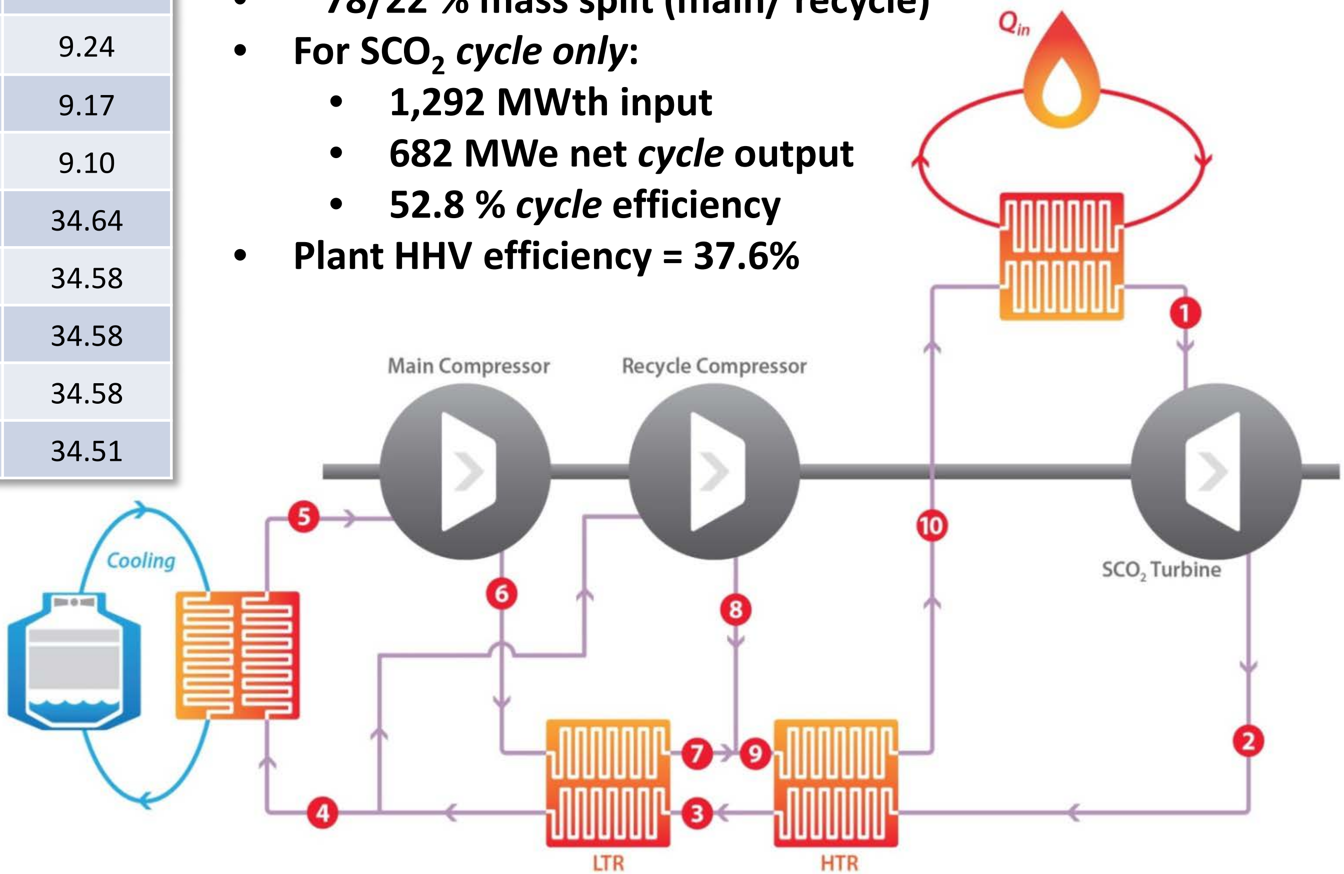
System Assumptions and Implications

- **Removal efficiency of in-bed limestone for B22A was pushed to 96% to meet SO2 emission limits with constant Ca/S ratio of 2.4**
  - Alstom air-CFB case assumes 90 percent SO2 removal
- **In-bed limestone was assumed to operate at a 94% single pass SO2 removal efficiency in the oxy case B22F**
  - In practice, recarbonation may limit the SO2 capture efficiency of in-bed limestone for oxy cases
- **Flue gas recycle for B22F was fixed at 45% of total flue gas**
  - Both the solids recycle (800°F) and flue gas recycle (135°F) work against maintaining a boiler exit temperature of 1,600°F
- **Several CFB design selections will be tied to a set of performance and cost, but in this case the modeled parameters and resulting performance are not reflected in the costs used**
  - The PA and FD fan discharge pressures reflect the pressure increases used in the Low Rank air-CFB cases, but do not reflect the Alstom cases
  - Boiler exit O2 mole percent of 1.9 was set to match the Oxy-PC reference case, and does not reflect the Alstom cases
  - Boiler carbon conversion target of 100 percent was set to match Oxy-PC reference, Alstom assumes 97.5 percent for both air and oxy-CFB

sCO_2 Case 2 State Points

State Point	Mass Flow	Temp.	Pressure
	Kg/s	° C	MPa
1	4131	760	34.37
2	4131	581	9.31
3	4131	235	9.24
4	3235	94	9.17
5	3235	35	9.10
6	3235	89	34.64
7	3235	230	34.58
8	896	230	34.58
9	4131	230	34.58
10	4131	532	34.51

- **Atmospheric pressure oxy-coal CFB combustor at AUSC conditions (Case 2)**
  - **Turbine inlet temp. = 1,400 °F (760 °C)**
  - **Pressure ratio ~ 3.7 (5015/1350 psia)**
- **10 X higher mass flow compared to steam**
- **~ 78/22 % mass split (main/ recycle)**
- **For SCO_2 *cycle only*:**
  - **1,292 MWth input**
  - **682 MWe net *cycle* output**
  - **52.8 % *cycle* efficiency**
- **Plant HHV efficiency = 37.6%**



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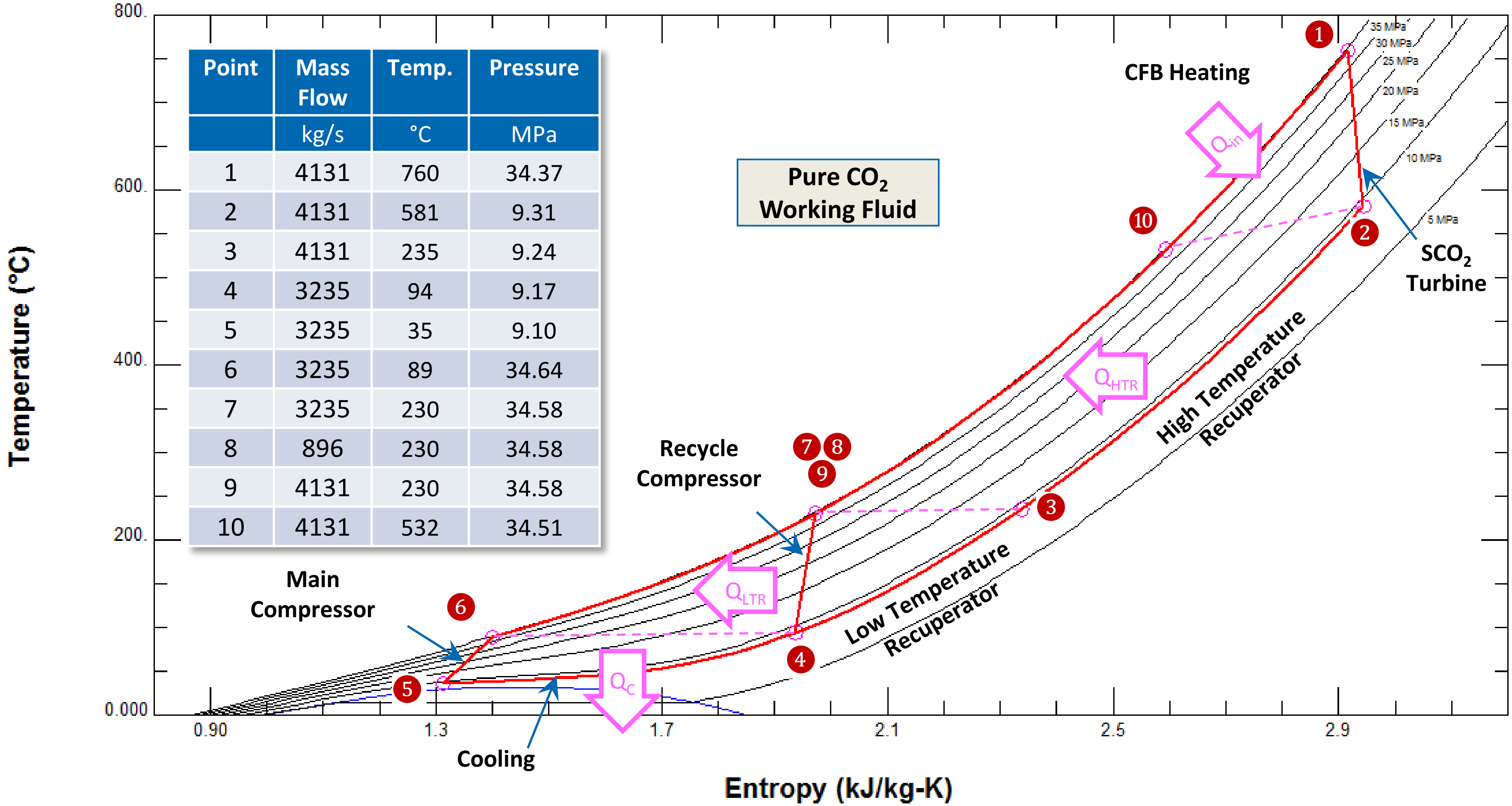
T-s Diagram for Case 2

- Thermal integration opportunities to improve overall system efficiency have not been explored
- Other heat sources may result in different efficiencies



Point	Mass Flow	Temp.	Pressure
	kg/s	°C	MPa
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7	3235	230	34.58
8	896	230	34.58
9	4131	230	34.58
10	4131	532	34.51

P-h Diagram for Case 2

- Thermal integration opportunities to improve overall system efficiency have not been explored
- Other heat sources may result in different efficiencies
- Max Pressure: 5015 psia
- Min Pressure: 1350 psia

Point	Mass Flow	Temp.	Pressure
	kg/s	°C	MPa
1	4131	760	34.37
2	4131	581	9.31
3	4131	235	9.24
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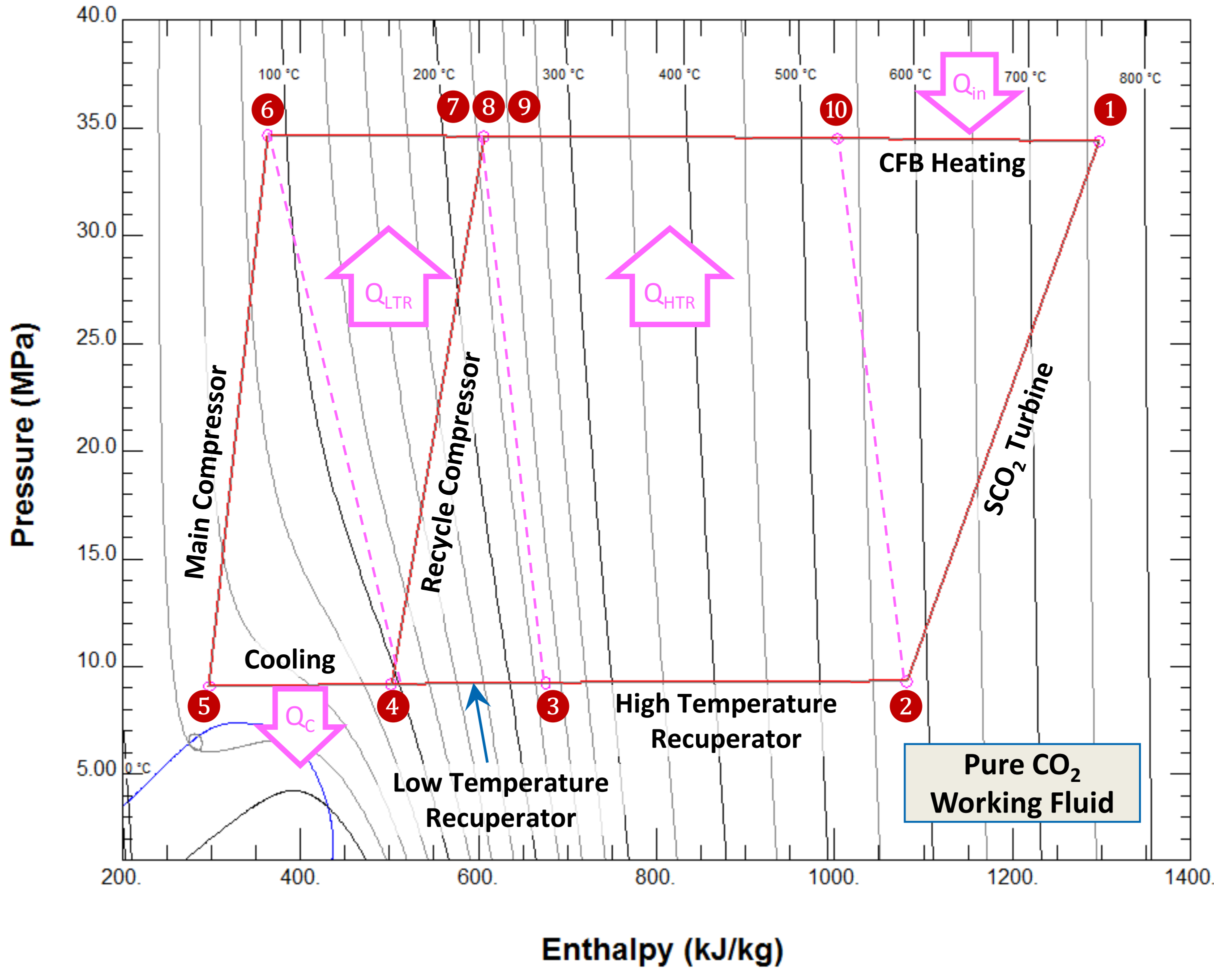
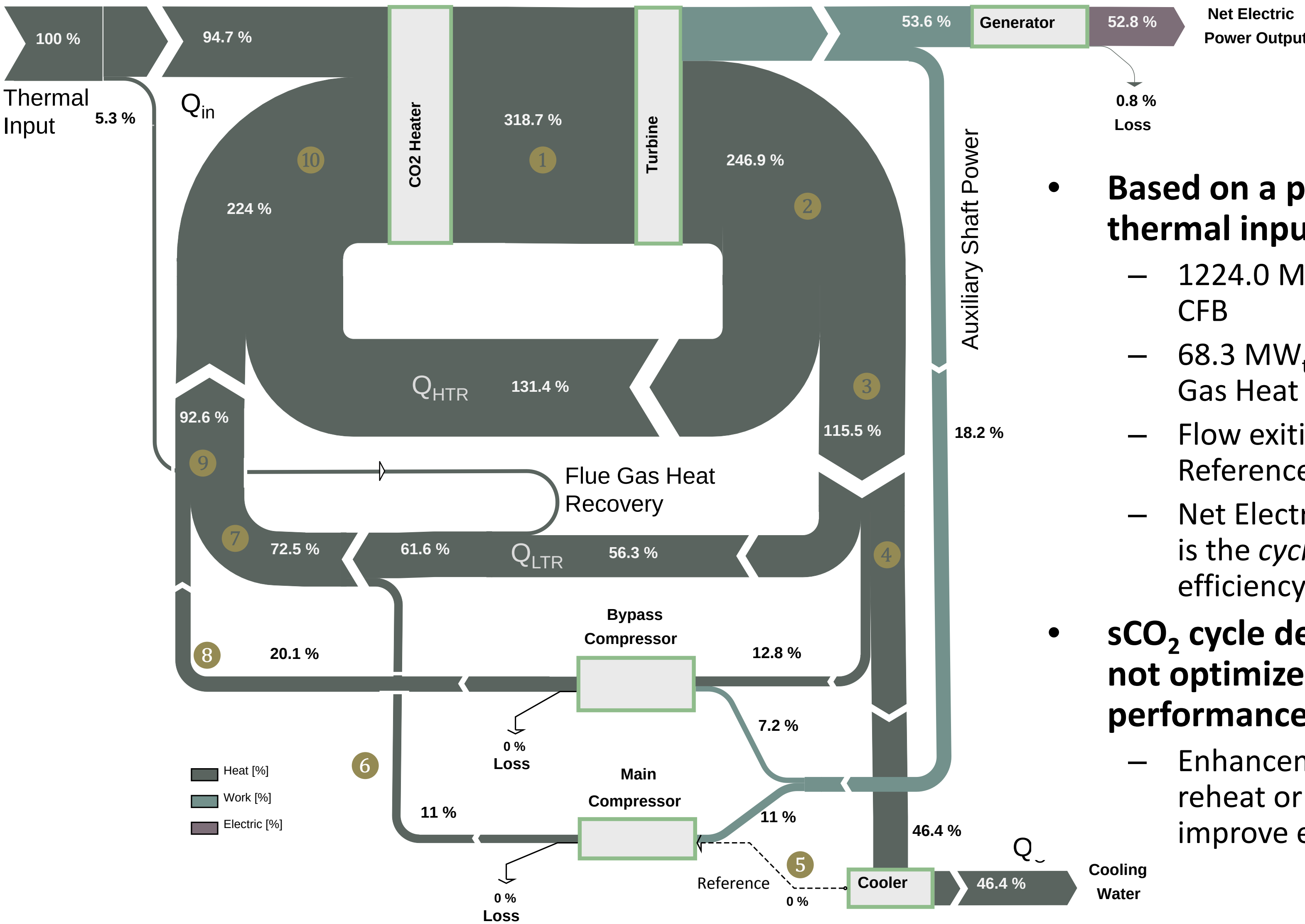
9	4131	230	34.58
10	4131	532	34.51



Case 2 Sankey Diagram of sCO_2 Cycle



- **Based on a percentage of thermal input:**
  - 1224.0 MW_{th} (94.7%) from CFB
  - 68.3 MW_{th} (5.3%) from Flue Gas Heat Recovery
  - Flow exiting Cooler used as Reference state
  - Net Electric Power Output is the *cycle* (not plant) efficiency
- **sCO_2 cycle depicted here is not optimized for performance**
  - Enhancements such as reheat or intercooling may improve efficiency