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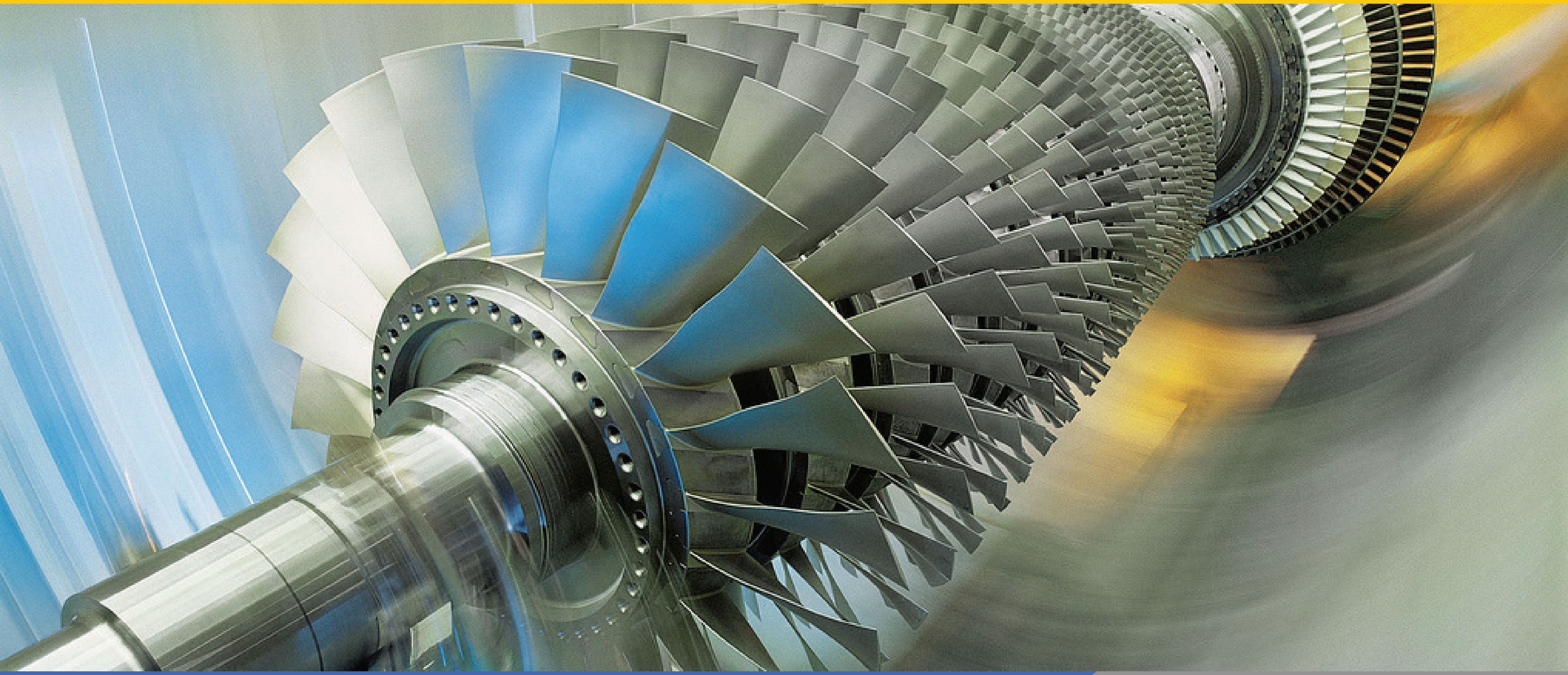

Performance of an Integrated Gasification Direct-Fired Supercritical CO_2 Power Cycle

Nathan Weiland, Wally Shelton, Chuck White

First Workshop on High Efficiency, Low Emissions Coal-Fired Plant (HELE2016)

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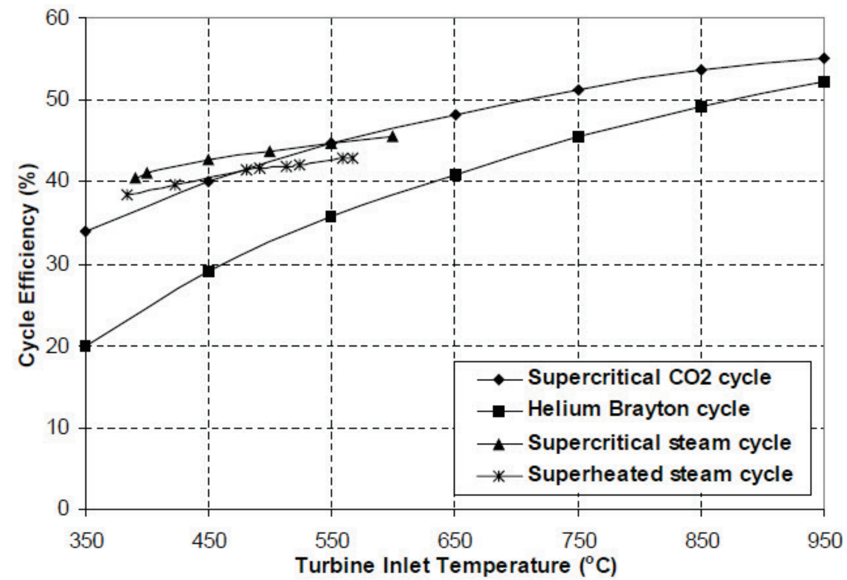
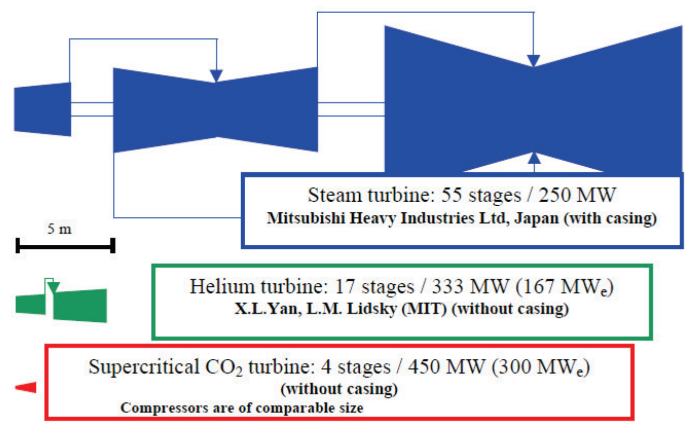
Why Supercritical CO_2 (sCO_2) Power Cycles?

- **Applicable to multiple heat sources (nuclear, solar, fossil, waste heat) for indirect heating**
- **Potential for higher efficiency relative to traditional power cycles**
  - High thermal recuperation rejects less heat to the environment
  - Single phase fluid heat transfer
  - Reduced cycle compression power near the CO_2 critical point
- **Reduced turbomachinery sizes due to higher working fluid density**
- **CO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O**





Source of Figures: 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.

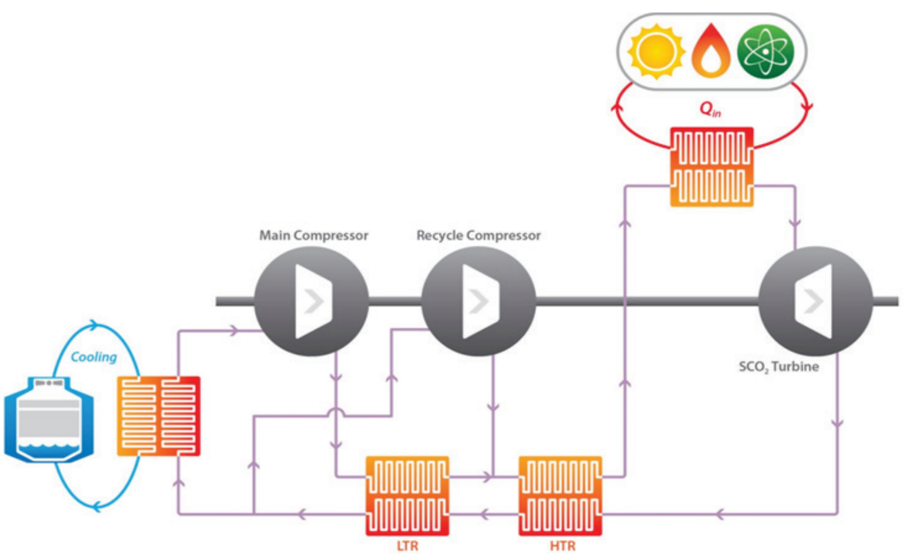
sCO_2 Cycles for Fossil Energy Applications

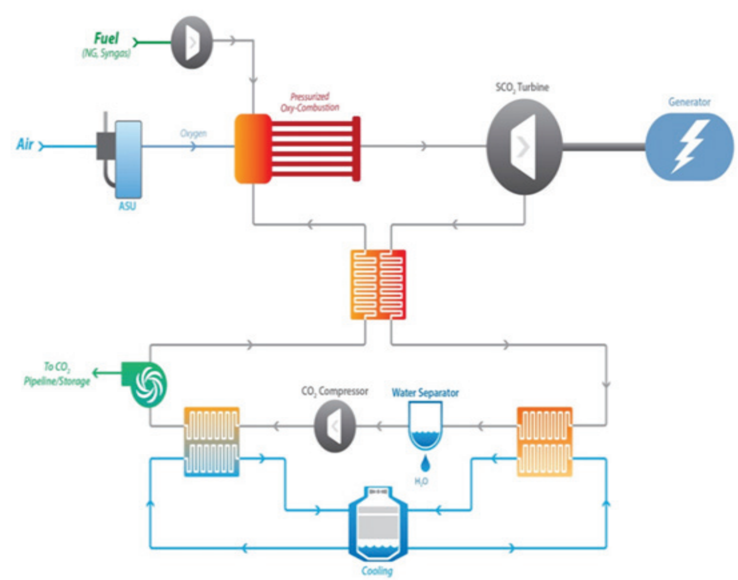
Indirectly-heated cycle

- Applicable to advanced combustion boilers
- Incumbent to beat: USC/AUSC boilers
- High fluid density, low pressure ratio yields compact turbomachinery
- Ideally suited to constant temp heat source
- Adaptable for dry cooling

Directly-heated cycle

- Applicable to IGCC and NGCC
- Incumbent to beat: Adv. F-, H-, or J- class Combined Cycle (NGCC or IGCC) w/ CCS
- Fuel flexible: coal syngas or NG
- 100% CO_2 capture at storage pressure
- Net water producer if air cooled



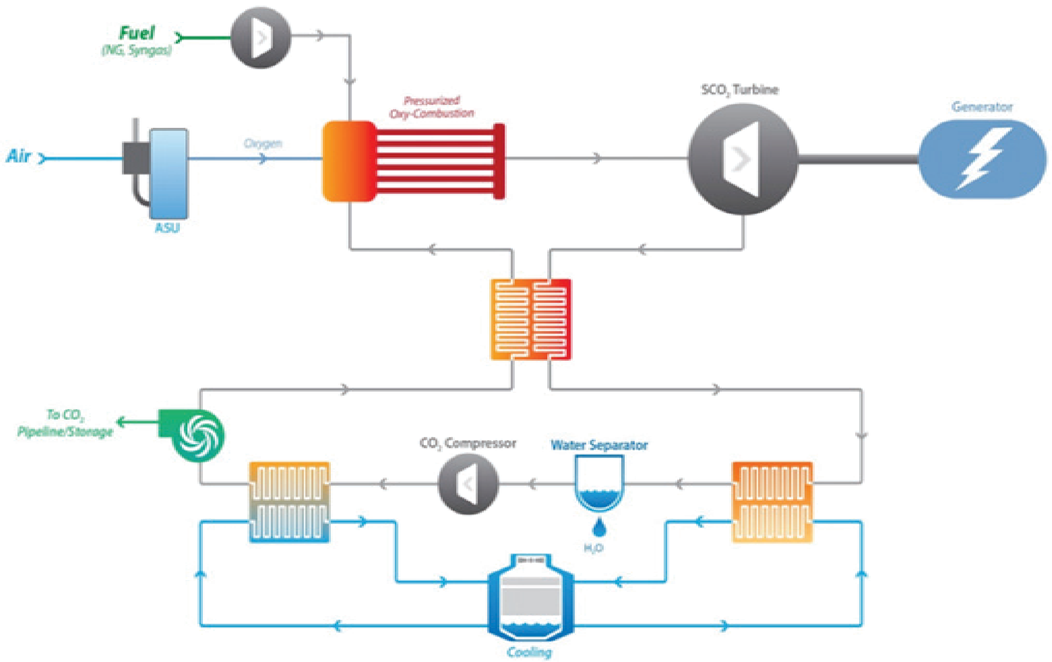


U.S. DOE Fossil Energy sCO_2 Power Cycle R&D Efforts

- **sCO_2 Power Cycles Base Program**
  - Implemented through multiple Fossil Energy programs
  - Combination of extramural projects and internal NETL research and analytical capabilities
    - Turbomachinery
    - Recuperators
    - Oxy-fuel Combustion
    - sCO_2 Heater Integration
    - Materials & Fundamentals
    - Systems Analysis
- **DOE sCO_2 Crosscut Initiative (STEP)**
  - Collaboration between Fossil, Nuclear & Renewable DOE Offices
  - Mission: Address technical issues, reduce risks, and mature technology to accelerate commercialization
  - Objective/goal: Design, build, and test 10 MWe pilot sCO_2 facility (STEP)
    - Conceptual design studies nearing completion
    - $100 Million, 6 year build and test program to start in 2016

Introduction to Direct sCO_2 Cycles

- **Direct-fired sCO_2 power cycles are attractive due to their high efficiency and inherent ability to capture CO_2 at storage-ready pressures**
- **High pressures lead to high power density and reduced footprint & cost**
- **Study Objectives:**
  - Develop a performance baseline for a syngas-fired direct sCO_2 cycle
  - Analyze sensitivity of performance and cost indicators to sCO_2 cycle parameters



Baseline Plant Assumptions

- **Generic Midwestern U.S. plant site[1]**
- **Illinois #6 bituminous coal[1]**
  - Lower moisture content
  - Better gasification performance
- **CO_2 purification unit (CPU) required to meet CO_2 pipeline purity specifications**
- **Plant sized for ~600 MW net power output**

Site Conditions	Midwest ISO
Elevation, m (ft)	0 (0)
Barometric Pressure, MPa (psia)	0.101 (14.7)
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)
Design Ambient Relative Humidity, %	60
Cooling Water Temperature, °C (°F)	15.6 (60)

Coal	Illinois #6	
Rank	HV Bituminous	
	As Rec'd.	Dry
Proximate Analysis (weight %)		
Moisture	11.12	0
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
HHV (kJ/kg)	27,113	30,506
LHV (kJ/kg)	26,151	29,444
Ultimate Analysis (weight %)		
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Oxygen	6.88	7.75

[1] *NETL, January 2012. Quality Guidelines for Energy System Studies. Pittsburgh, Pennsylvania.*

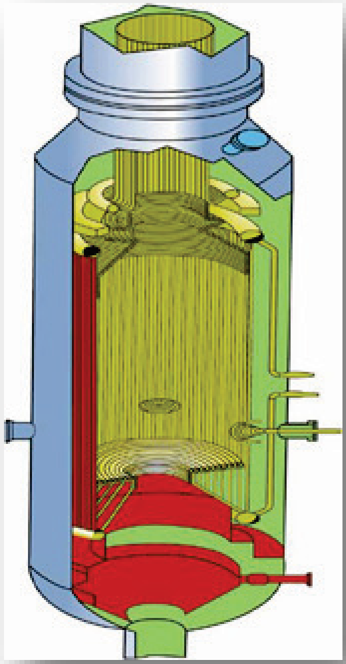
Gasification Comparison and Selection

GASIFIER	COAL TYPE	FEED SYSTEM	COAL DRYING	WASTE HEAT RECOVERY	COMMERCIAL OPERATION
GE RGC	bituminous	water slurry	no	yes	yes
GE QUENCH	bituminous	water slurry	no	no	yes
SHELL	bituminous subbituminous	lock hopper	yes	yes	yes
SIEMENS	bituminous subbituminous	lock hopper	yes	no	yes
E-GAS (CB&I)	bituminous subbituminous	water slurry	no	yes	yes
TRIG	subbituminous	lock hopper	yes	yes	no

- **Gasifier selection criteria:**
  - Minimize hydrogen content of syngas via coal drying and dry feeding
  - Recover syngas latent heat for raising steam and other thermal integration
  - Utilize a commercially-available, mature gasification process

Gasifier Train Design

- **Low pressure cryogenic Air Separation Unit (ASU)**
  - 204.5 kWh/tonne O_2 at 99.5% oxygen purity
  - High O_2 purity improves sCO_2 cycle performance by improving CO_2 purity and reducing compression power[2]
- **Shell gasifier selected**
  - Commercial offering with high cold gas efficiency
  - Includes high pressure dry coal feed system
    - Coal dried to 5% moisture by heated nitrogen from ASU
    - CO_2 transport gas for dried coal improves CO_2 purity for high sCO_2 cycle performance[2]
  - Entrained-flow, slagging gasifier with 99.5% carbon conversion
  - Syngas recycle stream to minimize ash agglomeration
  - Waste heat boiler recovers sensible heat from raw syngas for steam raising
- **Sulfur removal via Sulfinol process**
- **Sulfur recovery via oxygen-blown Claus unit**

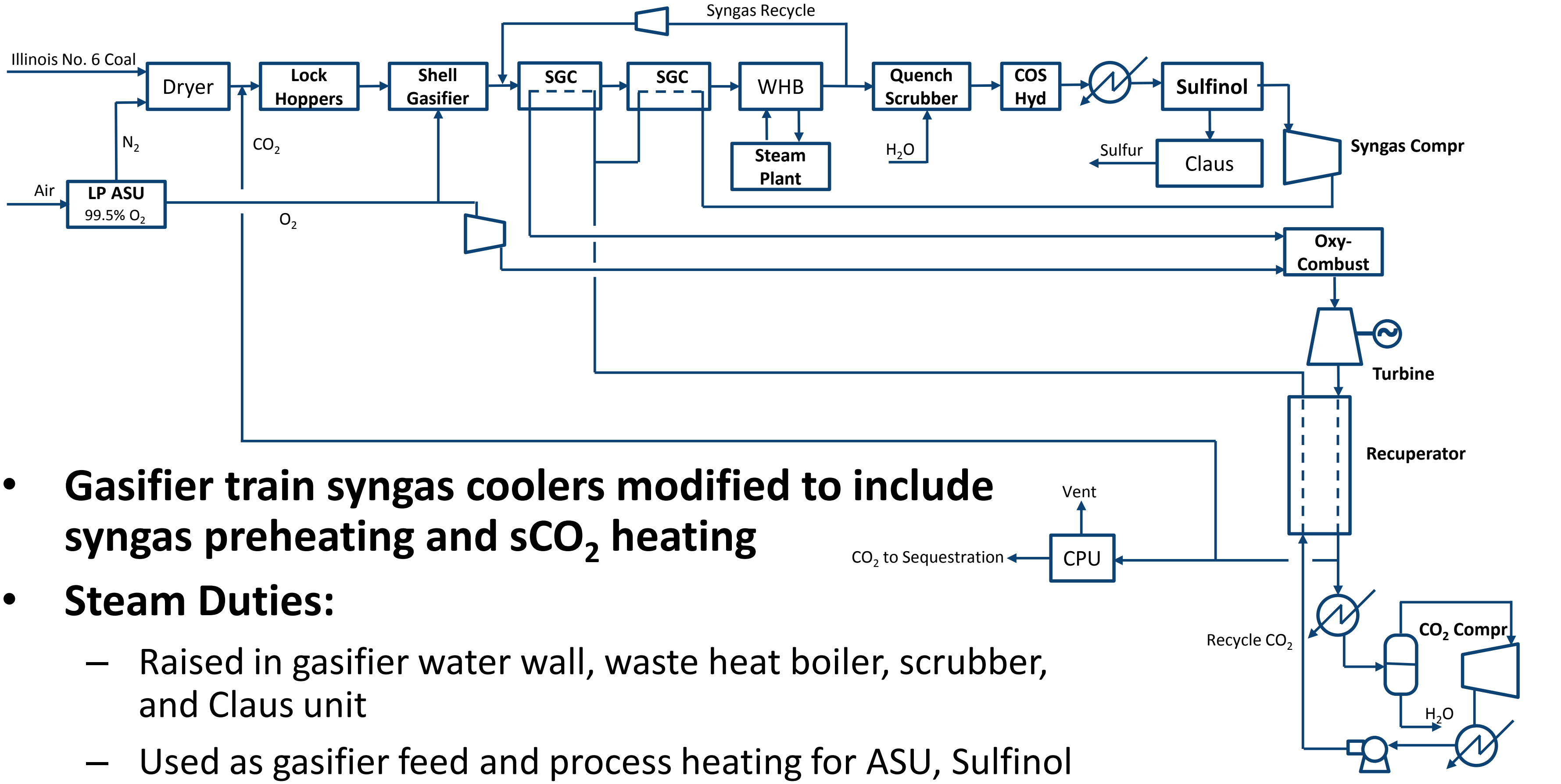


Shell Gasifier
(source: Shell)

[2] *Electric Power Research Institute (EPRI). (2014, December). Performance and Economic Evaluation of Supercritical CO2 Power Cycle Coal Gasification Plant (3002003734). Palo Alto, California.*

Coal-fired Direct sCO_2 Plant

Block Flow Diagram



- **Gasifier train syngas coolers modified to include syngas preheating and sCO_2 heating**
- **Steam Duties:**
  - Raised in gasifier water wall, waste heat boiler, scrubber, and Claus unit
  - Used as gasifier feed and process heating for ASU, Sulfinol reboiler, and sour water stripper reboiler
  - Not used for separate steam bottoming cycle to reduce cost

Modeling Assumptions for sCO_2 Cycle

- **Oxygen compressor**
  - 4-stage with three inter-coolers and an isentropic efficiency of 85%
  - Inter-cooler temperature 95 °F with water knock-out, 10 psi pressure drop
- **Syngas compressor**
  - 2-stage with single inter-cooler and an isentropic efficiency of 85%
  - Inter-cooler temperature 95 °F with water knock-out, 10 psi pressure drop
- **Syngas preheater temperature limited to 760 °C**
- **CO_2 heater (integrated with high temperature syngas cooler)**
  - Exit temperature set by pinch point analysis
- **Oxy-fired combustor includes Aspen generated combustion chemistry with NOx as NO and 100% conversion of combustible species**
- **sCO_2 turbine**
  - No blade cooling (in progress)
  - 98.5% generator efficiency
- **No heat losses from sCO_2 cycle components are assumed**

Baseline sCO_2 Cycle Parameters

Parameter	Initial Study[3]	Current Study
Cycle thermal input	1493 MW	1493 MW
Combustor pressure drop	0.7 bar	6.9 bar
Turbine inlet temperature	1149 °C	1149 °C
Turbine isentropic efficiency	0.927	0.927
Turbine exit pressure	30.0 bar	29.2 bar
Recuperator maximum temperature	760 °C	760 °C
Recuperator pressure drop per side	1.4 bar	1.4 bar
Minimum recuperator temperature approach	10 °C	10 °C
CO_2 cooler pressure drop	1.0 bar	1.0 bar
Cooler exit temperature	27 °C	27 °C
Compressor and pump isentropic efficiency	0.85	0.85
Nominal compressor pressure ratio	11.0	10.8
Compressor exit pressure	300 bar	300 bar

[3] *Weiland, N., Shelton, W.W., White, C., and D. Gray, "Performance Baseline for Direct-fired sCO_2 Cycles", The 5th International Symposium - Supercritical CO2 Power Cycles, San Antonio, TX, March 29-31, 2016.*

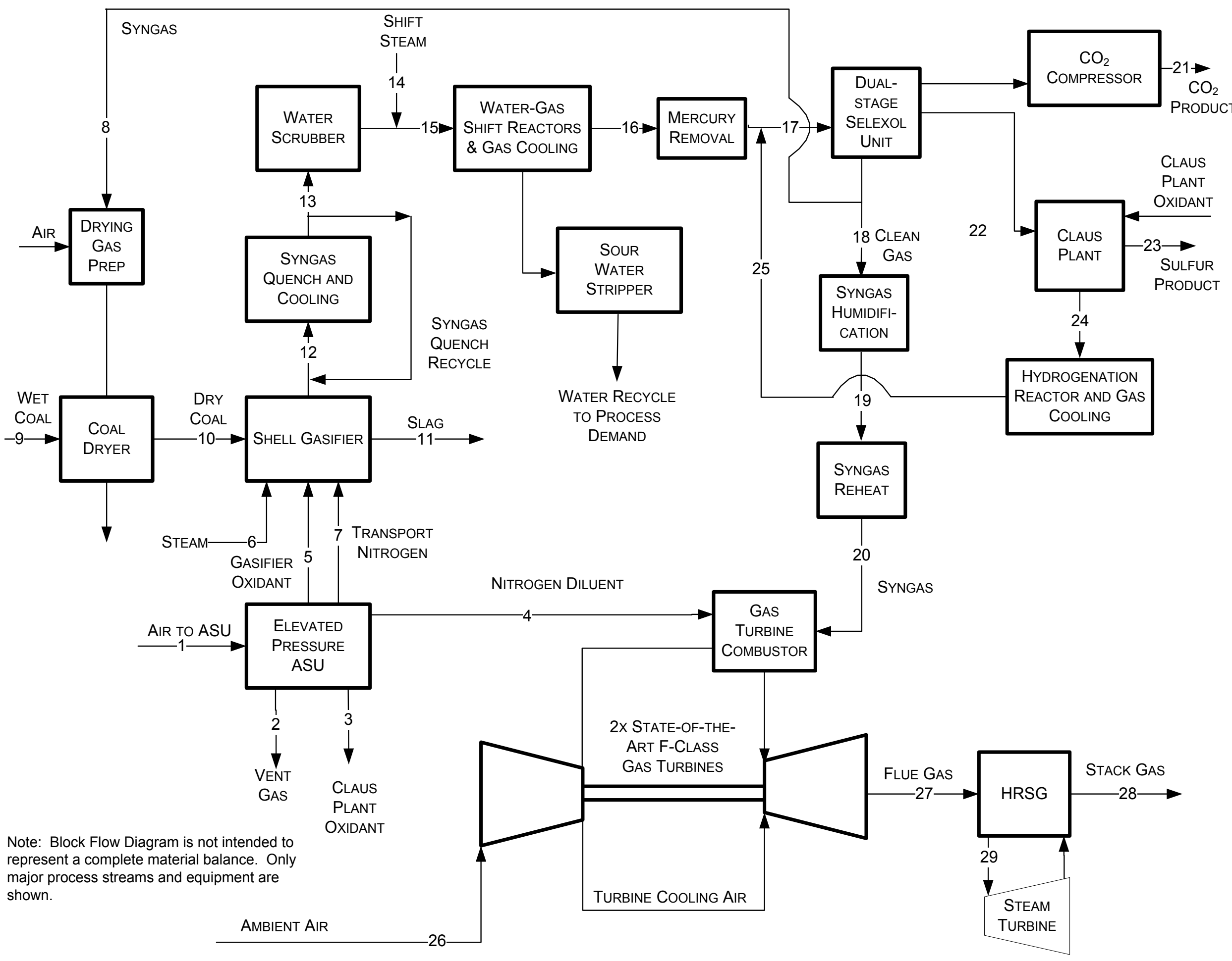
Modeling Details

- **Accurate system modeling depends critically on the ability of property methods to accurately capture large variations in CO_2 properties near its critical point (73.7 bar, 31 °C)**
  - REFPROP[4] is the most accurate property method for sCO_2, but cannot handle some coal combustion species (HCl, NH_3)
  - Initial study[3] and sensitivity analyses modeled in Aspen Plus® using the PR-BM (Peng-Robinson with Boston-Mathias alpha function) property method
  - Current study modeled in Aspen Plus® using the LK-PLOCK method
    - Lee-Kesler-Plöcker virial-type equation-of-state
    - NETL analysis shows this to be more accurate for direct fired sCO_2 cycles
- **Steady-state plant operation assumed**
- **Gasifier island model from prior model of non-capture Shell IGCC[5]**
  - Steam plant uses same approach as in the Shell IGCC study but with no steam turbine
- **CPU model from internal NETL study "Cost Breakdown of ASU and CPU Subsystems"**
- **Process heat integration scheme based on pinch point analysis with a minimum temperature approach of 14 °C**

[4] *Lemmon, E.W., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2013.*
[5] *National Energy Technology Laboratory (NETL). (2015, July 31). Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2b – Year Dollar Update. DOE/NETL-2015/1727, Pittsburgh, Pennsylvania.*

Reference Plant Description

- **IGCC power plant with carbon capture**
  - From NETL Bituminous Baseline Study[5], Case B1B
  - Illinois #6 coal
  - Shell gasifier
  - F-class turbine and steam bottom cycle
- **Differences:**
  - High pressure ASU with 95% O_2
  - Nitrogen used for coal transport and gas turbine combustion
  - Water-gas shift and CO_2 removal



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

[5] National Energy Technology Laboratory (NETL). (2015, July 31). Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2b – Year Dollar Update. DOE/NETL-2015/1727, Pittsburgh, Pennsylvania.

Preliminary Performance Comparison

- **sCO_2 plant achieves greater efficiency, 39.8% vs. 31.2%, due to differences in cycle efficiencies**
  - Generates 20% more power
  - Requires 6% percent less coal
- **sCO_2 plant achieves greater carbon capture fraction**
  - IGCC capture limited by water-gas shift reaction and Selexol process
- **Similar results obtained in 2014 EPRI study[2]**
  - sCO_2 net HHV plant efficiency of 39.6% with 99.2% CO_2 capture at 98.1% purity
  - Includes steam bottoming cycle

Parameter	IGCC[5]	sCO_2 Cycle
Coal flow rate (kg/hr)	211,040	198,059
Oxygen flow rate (kg/hr)	160,514	391,227
sCO_2 flow rate (kg/hr)	---	6,669,350
Carbon capture fraction (%)	**90.1**	**98.1**
Captured CO_2 purity (mol% CO_2)	99.99	99.44
Net plant efficiency (HHV %)	**31.2**	**39.8**
sCO_2 power cycle efficiency (%)	---	55.5
F-frame gas turbine efficiency (HHV %)	35.9	---
Steam power cycle efficiency (%)	39.0	---
Raw water withdrawal (m^3/s)	0.355	0.344
Carbon conversion (%)	99.5	99.5
Power summary (MW)		
Coal thermal input (HHV)	1,591	1,493
Steam turbine power output	209	0
Gas turbine power output	464	0
sCO_2 turbine power output	0	789
Gross power output	673	789
Total auxiliary power load	177	195
Net power output	**497**	**595**

[2] *Electric Power Research Institute (EPRI). (2014, December). Performance and Economic Evaluation of Supercritical CO2 Power Cycle Coal Gasification Plant (3002003734). Palo Alto, California.*

[5] *National Energy Technology Laboratory (NETL). (2015, July 31). Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2b – Year Dollar Update. DOE/NETL-2015/1727, Pittsburgh, Pennsylvania.*

Preliminary Auxiliary Power Comparison

- **Both plants require about 25% of gross power output for auxiliaries**
- **IGCC requires:**
  - Higher acid gas removal power to remove CO_2 from syngas
  - High nitrogen compression power
- **sCO_2 cycle has:**
  - Higher ASU and oxygen compressor power requirement for oxy-combustion
  - Lower CPU requirement due to high CO_2 pressure
- **Fraction of cycle gross power for cycle compression (not shown):**
  - sCO_2 cycle: 15.4%
    - Compressor: 88 MW
    - Pump: 58 MW
  - Gas turbine: >30%

Auxiliary Load (MW)	IGCC[5]	sCO_2 Cycle
Coal milling & handling, slag handling	3.2	3.0
Air separation unit auxiliaries	1.0	1.0
Air separation unit main air compressor	59.7	79.0
Gasifier oxygen compressor	9.5	19.9
sCO_2 oxygen compressor	---	25.8
Nitrogen compressors	32.9	---
Fuel gas compressor	---	34.7
CO_2 compressor (including CPU)	30.2	16.6
Boiler feedwater pumps	3.5	0
Syngas recycle compressor	0.8	0.9
Circulating water pump	4.4	3.4
Cooling tower fans	2.3	2.2
Acid gas removal	18.7	0.5
Gas/sCO_2 turbine auxiliaries	1.0	1.0
Claus plant TG recycle compressor	1.8	0.6
Miscellaneous balance of plant	5.1	3.5
Transformer losses	2.5	2.9
TOTAL	**176.5**	**195.0**

[5] National Energy Technology Laboratory (NETL). (2015, July 31). Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2b – Year Dollar Update. DOE/NETL-2015/1727, Pittsburgh, Pennsylvania.

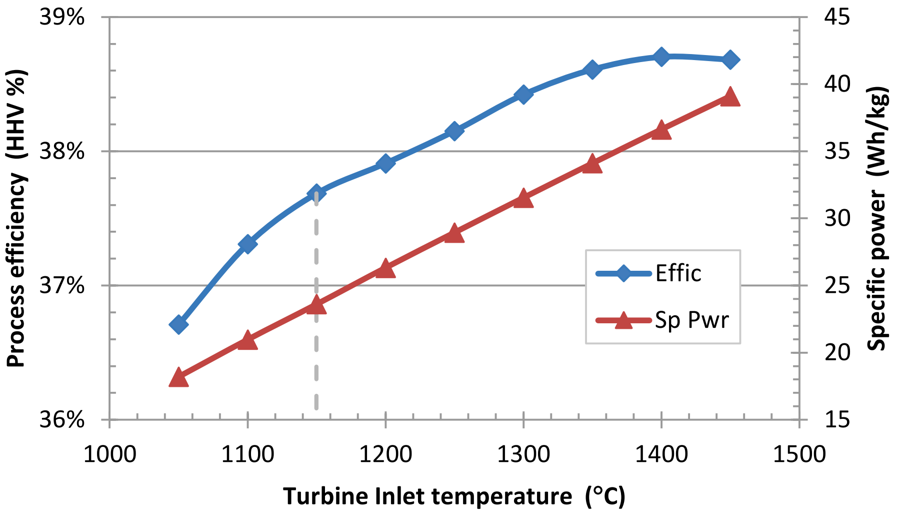
Sensitivity Analyses[3]

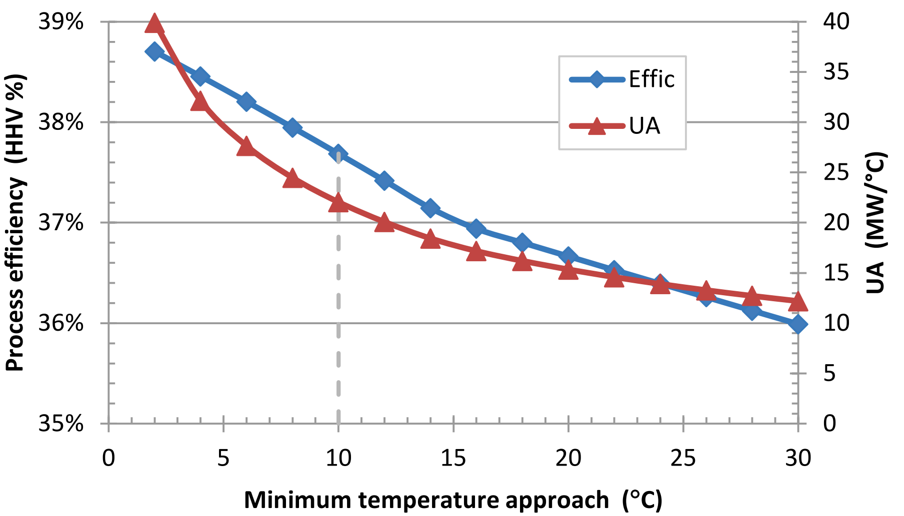
- **Performed sensitivity analyses in our initial study[3] on several cycle parameters**
  - Turbine exit pressure
  - Turbine inlet temperature
  - Compressor exit pressure
  - CO_2 cooler temperature
  - CO_2 cooler pressure
  - Cycle pressure drop
  - Minimum recuperator approach temperature
  - CO_2 compressor & pump intercooling (present study)
  - Excess oxygen in combustor (negligible effect for 0 – 5%)
- **All other cycle parameters remain fixed in sensitivity analyses**

[3] *Weiland, N., Shelton, W.W., White, C., and D. Gray, "Performance Baseline for Direct-fired sCO_2 Cycles", The 5th International Symposium - Supercritical CO2 Power Cycles, San Antonio, TX, March 29-31, 2016.*

Sensitivity Analyses (cont.)

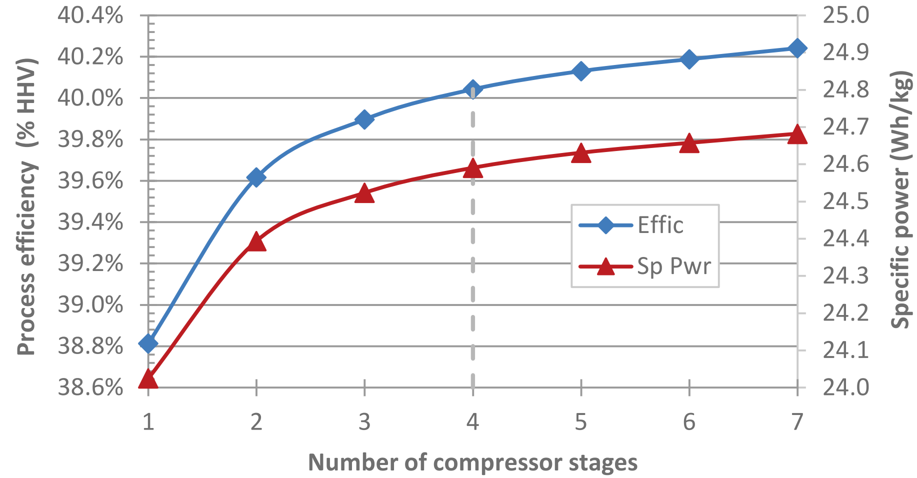
- **Turbine inlet temperature:**
  - Turbine exit pressure adjusted to yield exit temperature of 760 °C
  - Increasing turbine inlet temp.:
    - Increases pressure ratio
    - Increases required fuel and oxidizer, reducing sCO_2 purity
    - Increases specific power
  - Must account for cost of materials and blade cooling
- **Minimum recuperator approach temperature**
  - Large efficiency benefit to decreased approach temperatures
  - Low approach temperatures expected to significantly increase recuperator capital cost, directly related to surface area (UA)
  - No specific power dependence

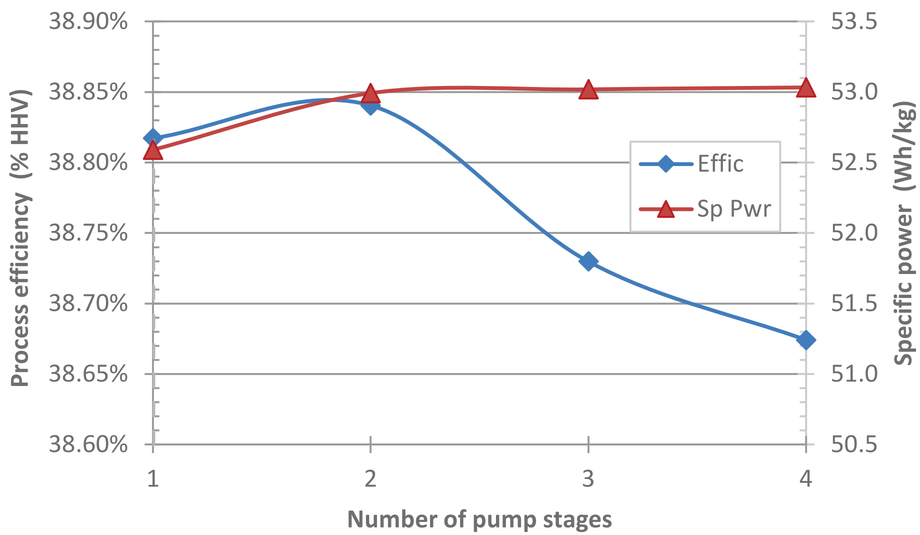




Sensitivity Analyses (cont.)

- **Performed in the current study (LK-PLOCK property method)**
- **Pre-compressor stages**
  - Between each stage, intercooler used with temperature 27 °C and pressure drop 0.14 bar
  - Large increases in efficiency, lesser increases in specific power
  - 4 stages and 3 intercoolers selected for Baseline case
- **Final pump stages**
  - Between each stage, intercooler used with temperature 27 °C and pressure drop 0.14 bar
  - Minimal increase in efficiency with 2 stages, small increase in specific power with stages
  - 1 stage and 0 intercoolers selected for Baseline case

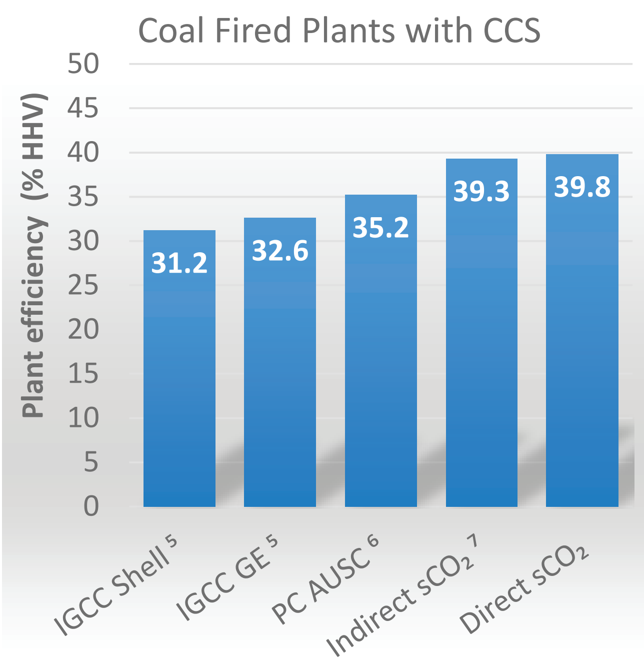




Conclusions and Future Work

- **Conclusions:**
  - Direct coal-fired sCO_2 cycle developed shows improved performance relative to IGCC and other reference cases
  - Capital costs are expected to be lower than IGCC due to replacement of gas turbine and steam bottoming cycle
  - Sensitivity studies provide guidelines for improving performance and reducing costs
- **Future Work**
  - Incorporate the effects of turbine blade cooling flows
  - Develop cost estimate for the improved baseline case
  - Extend analyses to development of natural gas-fired direct sCO_2 cycles

Parameter	IGCC	sCO_2 Cycle	EPRI sCO_2 Cycle[2]
Net power output (MWe)	497	595	583
Net plant efficiency (HHV %)	31.2	39.8	39.6
Carbon capture fraction (%)	90	98	99
Captured CO_2 purity (mol% CO_2)	99.99	99.44	98.1



[5] National Energy Technology Laboratory (NETL). (2010, November 2). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Pittsburgh, Pennsylvania.
[6] Weiland, N., and Shelton, W. W. "Systems Analyses of Direct Power Extraction (DPE) and Advanced Ultra-Supercritical (AUSC) Power Plants," Crosscutting Research & Rare Earth Elements Portfolios Review, Pittsburgh, PA, April 18th, 2016.
[7] Shelton, W. W., Weiland, N., White, C., Plunkett, J., and D. Gray. Oxy-coal-fired Circulating Fluid Bed Combustion with a Commercial Utility-size Supercritical CO2 Power Cycle. The 5th International Symposium - Supercritical CO2 Power Cycles. San Antonio, Texas. March 2016.

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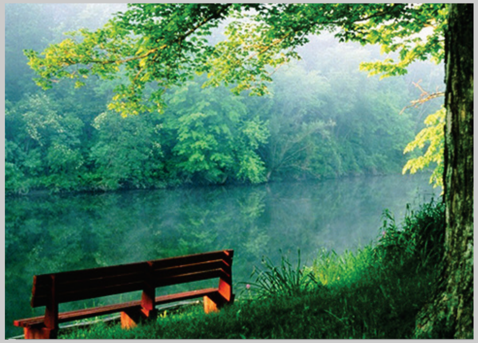

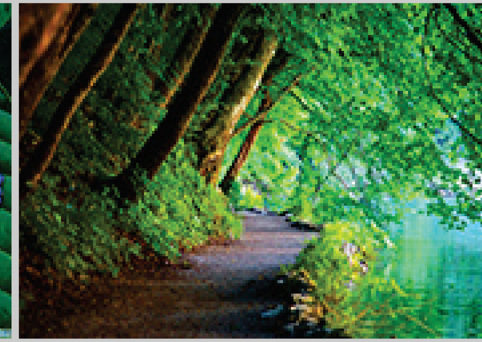

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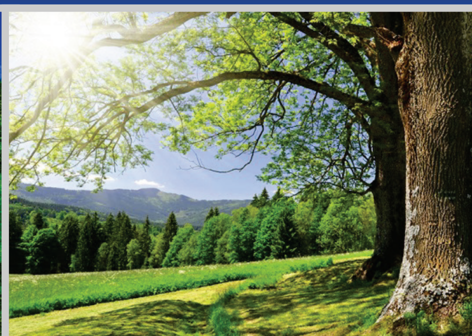
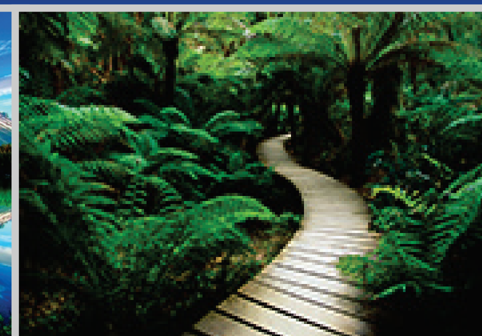
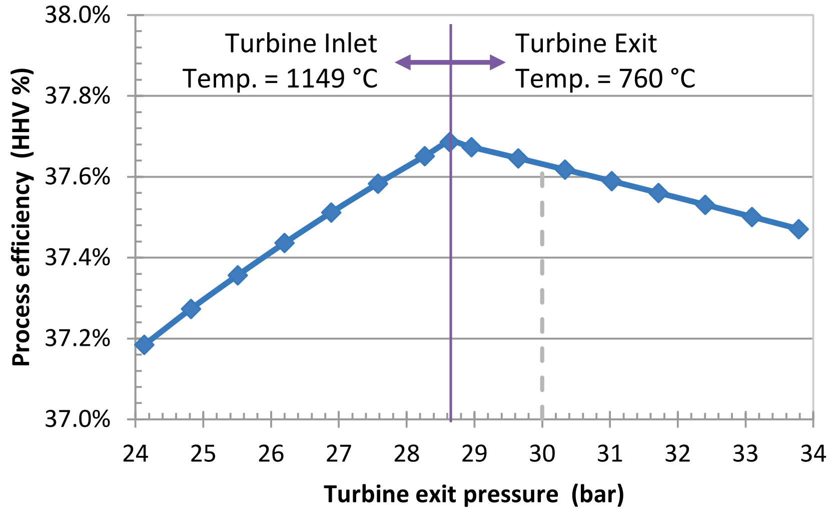
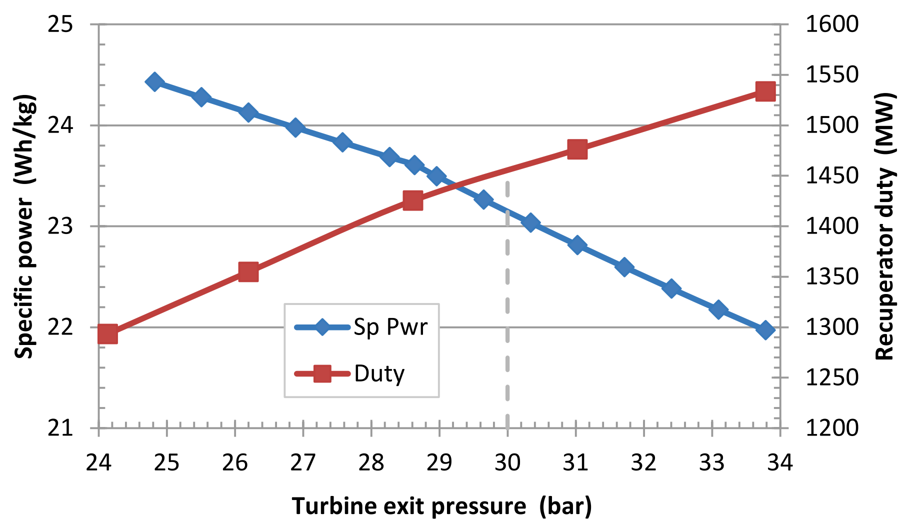




Sensitivity Analyses (cont.)

- **For sensitivity to turbine exit pressure, all other parameters kept constant except …**
  – Turbine exit temperature limited to 760 °C
  – Turbine inlet temperature limited to 1149 °C
  – CO_2 purge fraction adjusted to attain limiting turbine inlet or exit temperature
- **Maximum process efficiency occurs at turbine exit pressure of 28.6 bar, where both turbine inlet and exit temperature constraints are met**
- **Below 28.6 bar:**
  – Turbine exit temperature decreases as turbine exit pressure decreases
  – Higher specific power and lower recuperator duty reduce cycle cost
- **Above 28.6 bar:**
  – Turbine inlet temperature and cycle efficiency decreases as turbine exit pressure increases
  – Increasing recuperator duty and reduced specific power will increase cycle cost





Sensitivity Analyses (cont.)

- **CO_2 Cooler Temperature**
  - Demonstrates the benefit of operating in a condensing sCO_2 cycle to reduce compression power requirements
  - Does not account for needed refrigeration at low temperature
- **CO_2 Cooler Pressure**
  - Intermediate pressure between the sCO_2 compressor and pump
  - Efficiency and specific power maxima near critical pressure of 73.9 bar
- **High uncertainty in these results due to the use of PR-BM property method near the CO_2 critical point (31 °C, 73.9 bar)**