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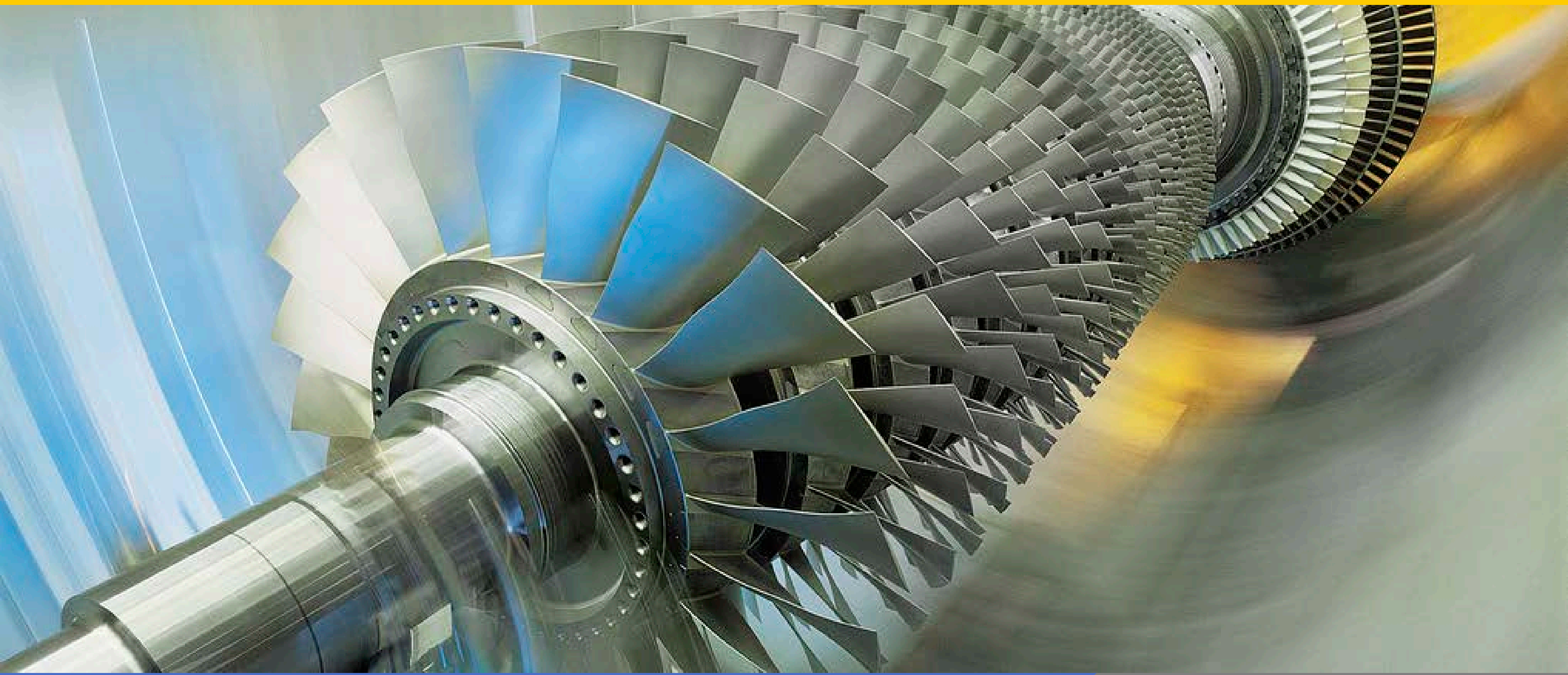

Performance Baseline for Direct-Fired sCO_2 Cycles

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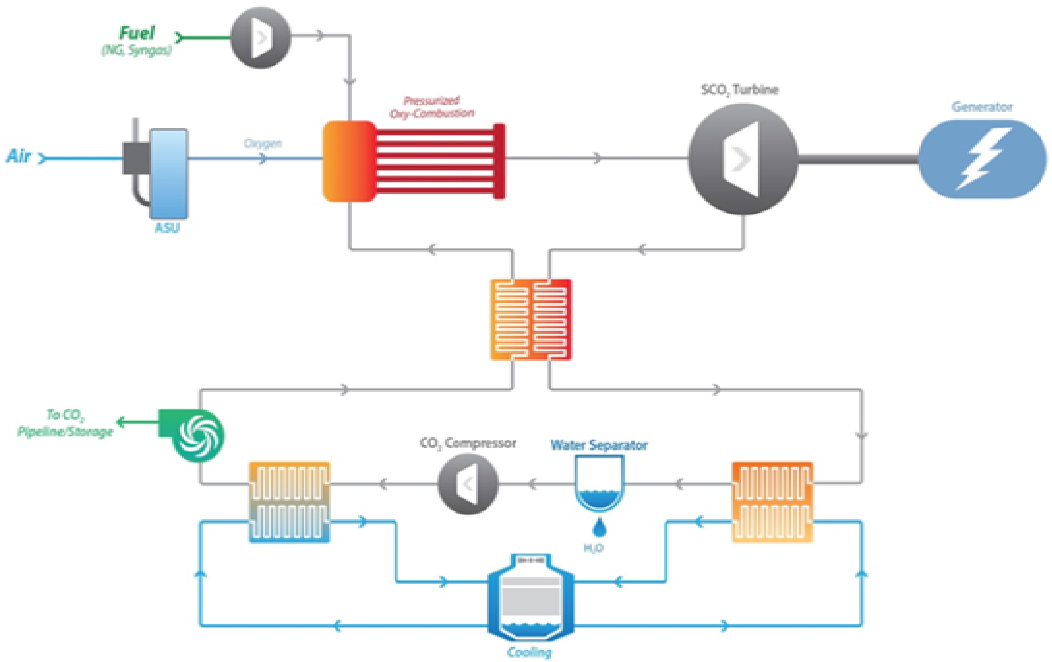
Introduction

- **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 plant site**
- **Illinois #6 bituminous coal**
  - 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

Gasification Technology, Coal Rank and Gas Cleaning Options

GASIFIER	COAL TYPE	FEED SYSTEM	COAL DRYING	WASTE HEAT RECOVERY	COMMENTS
GE RGC	bituminous	water slurry	no	yes	Warm gas clean-up (WGCU), steam cycle or recuperation opportunities
GE QUENCH	bituminous	water slurry	no	no	Conventional syngas cleaning
SHELL	bituminous subbituminous	lock hopper	yes	yes	WGCU, steam cycle or recuperation opportunities
SIEMENS	bituminous subbituminous	lock hopper	yes	no	Conventional syngas cleaning
E-GAS (CB&I)	bituminous subbituminous	water slurry	no	yes	WGCU, steam cycle or recuperation opportunities
TRIG	subbituminous	lock hopper	yes	yes	WGCU, steam cycle or recuperation opportunities

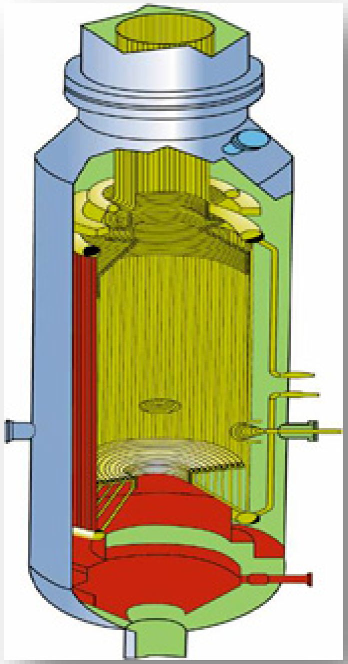
Syngas-Fired sCO_2 Cycle Configurations

Pros and Cons

Config	Description	Coal	Pros	Cons
1	Shell gasifier, Waste heat boiler (WHB), WGCU	Bit	Shell gasification has high cold gas efficiency Illinois coal has lower moisture thus less energy is needed for drying to 6 percent CO_2 transport gas eliminates gasifier steam WHB recovers sensible heat from raw syngas for steam cycle WGCU produces moisture free syngas WGCU has lower cost than conventional cleaning	Shell gasification with WHB has high capital cost WGCU not commercially tested Need to dry coal
2	Shell gasifier, WHB, conventional gas cleaning	Bit	Shell gasification has high cold gas efficiency Illinois coal has lower moisture thus less Energy is needed for drying to 6 percent CO_2 transport gas eliminates gasifier steam WHB recovers sensible heat from raw syngas for steam cycle CGCU is conventional technology	Syngas has diminished thermodynamic availability Studies show WGCU more economical Need to dry coal
3	TRIG gasifier, syngas cooler (SGC), WGCU	PRB	Depending on plant location PRB coal could be cheaper TRIG uses coarser coal thus less grinding energy TRIG can accept 18 % moisture coal less drying TRIG is suitable for highly reactive PRB coal TRIG operates at lower temperature less O_2 SGC recovers sensible heat from raw syngas for steam cycle Low cost coal	TRIG not commercially tested Less recoverable syngas heat than Config 1 WGCU not commercially tested
4	Siemens gasifier, quench, conventional gas cleaning	Bit	Siemens quench gasification has low capital cost Relatively high cold gas efficiency Overall simpler system Best option to eliminate Rankine cycle	Quench operation does not recover raw syngas sens. heat Lower overall efficiency system Need to dry coal

Gasifier Train Design

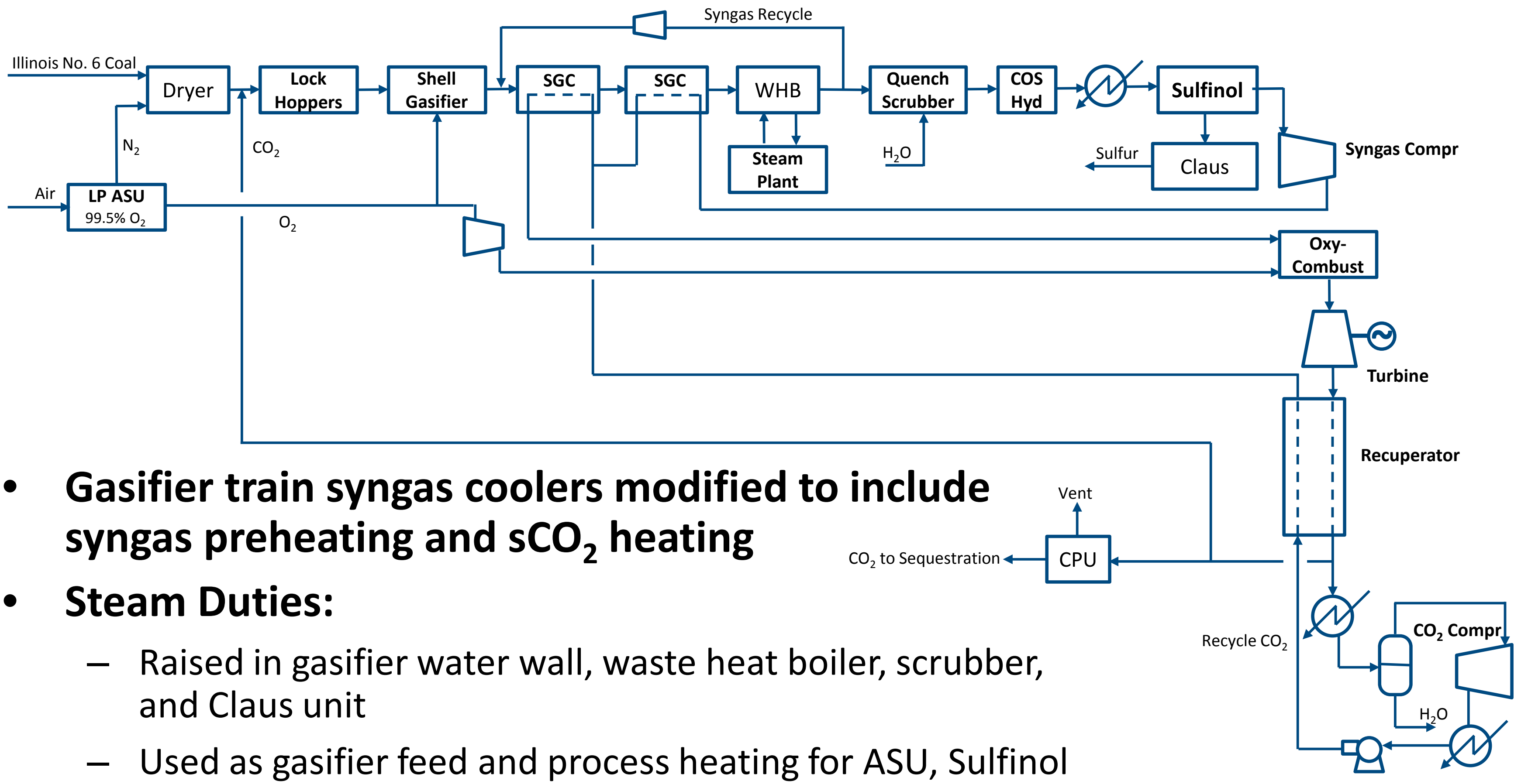
- **Low pressure cryogenic Air Separation Unit (ASU)**
  - 204.5 kWh/tonne O_2 at 99.5% oxygen purity
  - High O_2 purity improves sCO_2 cycle performance by improving CO_2 purity and reducing compression power (EPRI, 2014)
- **Shell gasifier selected**
  - Commercial offering with high cold gas efficiency
  - 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 (EPRI, 2014)
  - 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 Selexol/Sulfinol process**
- **Sulfur recovery via oxygen-blown Claus unit**



Shell Gasifier
(source: Shell)

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 power 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
  - 98.5% generator efficiency
- **No heat losses from sCO_2 cycle components are assumed**

Baseline sCO_2 Cycle Parameters

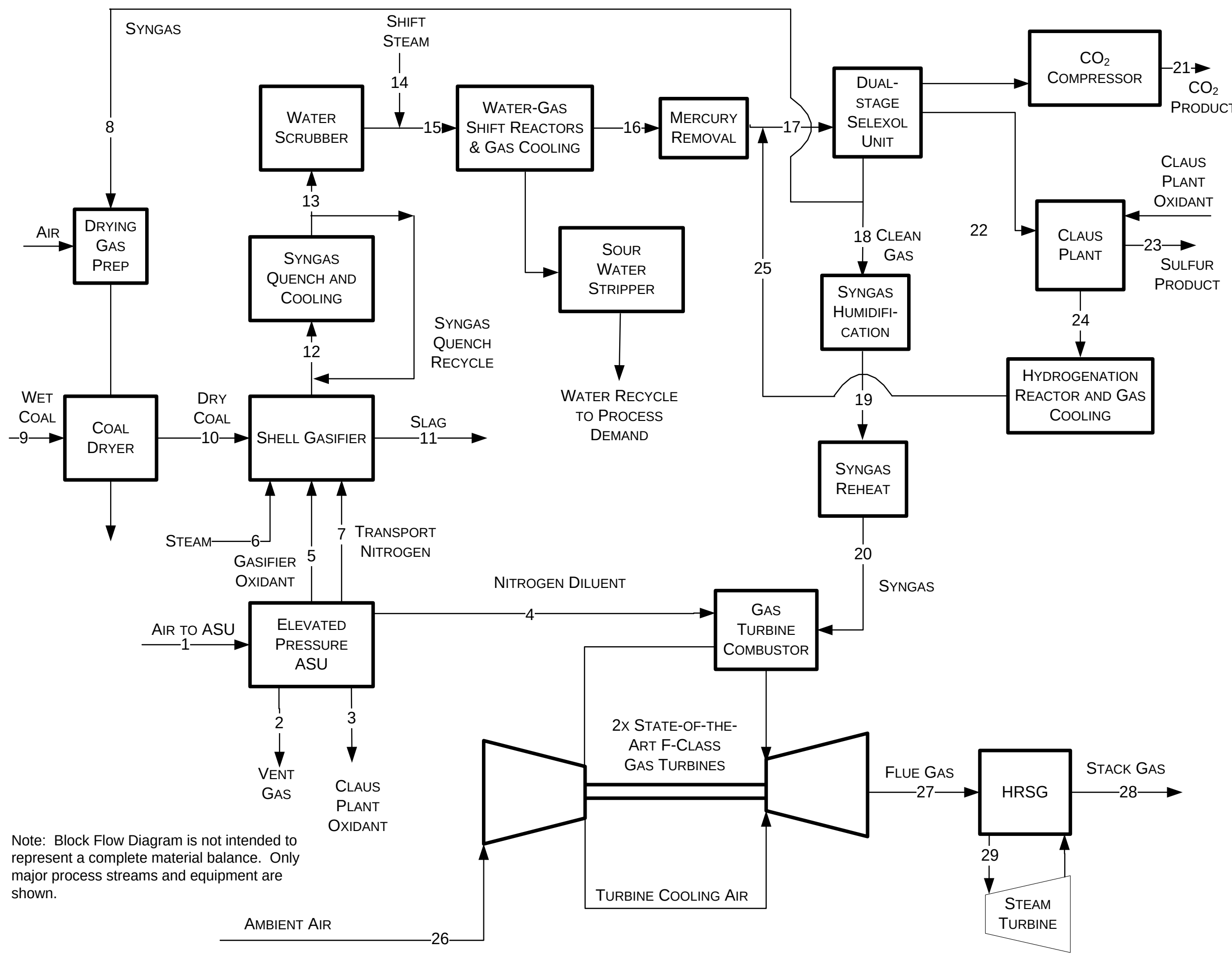
Parameter	Value (SI)	Value (English)
Cycle thermal input	1315 MW	4487 MMBtu/hr
Combustor pressure drop	0.7 bar	10 psia
Turbine inlet temperature	1149 °C	2100 °F
Turbine isentropic efficiency	0.927	0.927
Turbine exit pressure	30.0 bar	435 psia
Recuperator maximum temperature	760 °C	1400 °F
Recuperator pressure drop per side	1.4 bar	20 psia
Minimum recuperator temperature approach	10 °C	18 °F
CO_2 cooler pressure drop	1.4 bar	20 psia
Cooler exit temperature	27 °C	80 °F
Compressor and pump isentropic efficiency	0.85	0.85
Nominal compressor pressure ratio	11.0	11.0
Compressor exit pressure	300 bar	4351 psia

Modeling Details

- **Modeled in Aspen Plus® using the PR-BM method**
  - Peng-Robinson with Boston-Mathias alpha function
  - REFPROP unavailable due to presence of HCl and NH_3
- **Steady-state operation assumed**
- **Gasifier island model from prior Noblis model of non-capture Shell IGCC**
- **Steam plant uses same approach as in above study but with no steam turbine**
- **CPU model from internal NETL study "Cost Breakdown of ASU and CPU Subsystems"**
- **Heat integration scheme based on pinch point analysis with a minimum temperature approach of 25 °F**

Reference Plant Description

- **IGCC power plant with carbon capture**
  - From NETL Bituminous Baseline Study, Case 6
  - 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



Performance Comparison

- **sCO_2 plant achieves greater efficiency, 37.7% vs. 31.2%, due to differences in cycle efficiencies**
  - Generates 13% 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**
  - 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	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)	---	6,608,538
Carbon capture fraction (%)	**90.1**	**98.1**
Captured CO_2 purity (mol% CO_2)	99.99	99.44
Net plant efficiency (HHV %)	**31.2**	**37.7**
sCO_2 power cycle efficiency (%)	---	53.1
F-frame gas turbine efficiency (HHV %)	35.9	---
Steam power cycle efficiency (%)	39.0	---
Raw water withdrawal (m^3/s)	0.355	0.360
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	758
Gross power output	673	758
Total auxiliary power load	177	196
Net power output	**497**	**563**

Auxiliary Power Comparison

- **Both plants require about 26% 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: 19.3%
    - Compressor: 109 MW
    - Pump: 72 MW
  - Gas turbine: >30%

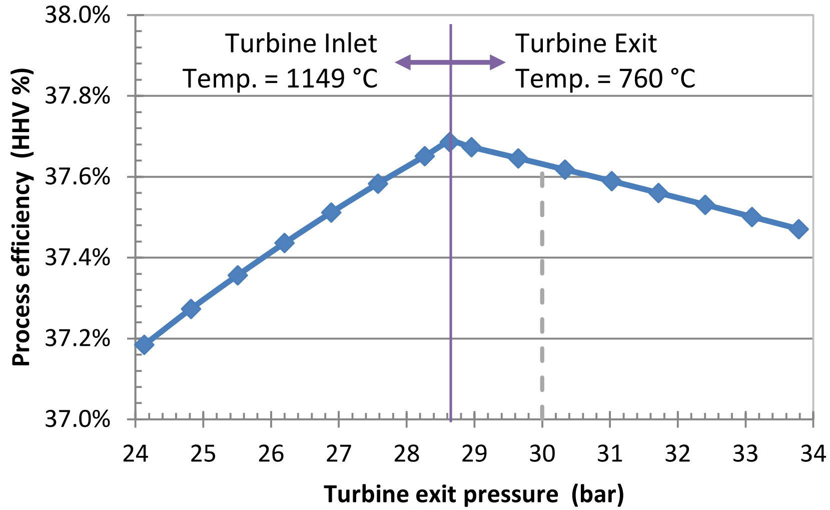
Auxiliary Load (MW)	IGCC	sCO_2 Cycle
Coal milling & handling, slag handling	3.2	3.0
Air separation unit auxiliaries	1.0	1.0
Air separation unit main air compressor	59.7	79.0
Gasifier oxygen compressor	9.5	19.9
sCO_2 oxygen compressor	---	25.7
Nitrogen compressors	32.9	---
Fuel gas compressor	---	34.2
CO_2 compressor (including CPU)	30.2	17.0
Boiler feedwater pumps	3.5	0
Syngas recycle compressor	0.8	0.9
Circulating water pump	4.4	3.6
Cooling tower fans	2.3	2.3
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	4.1
Transformer losses	2.5	2.8
TOTAL	**176.5**	**195.6**

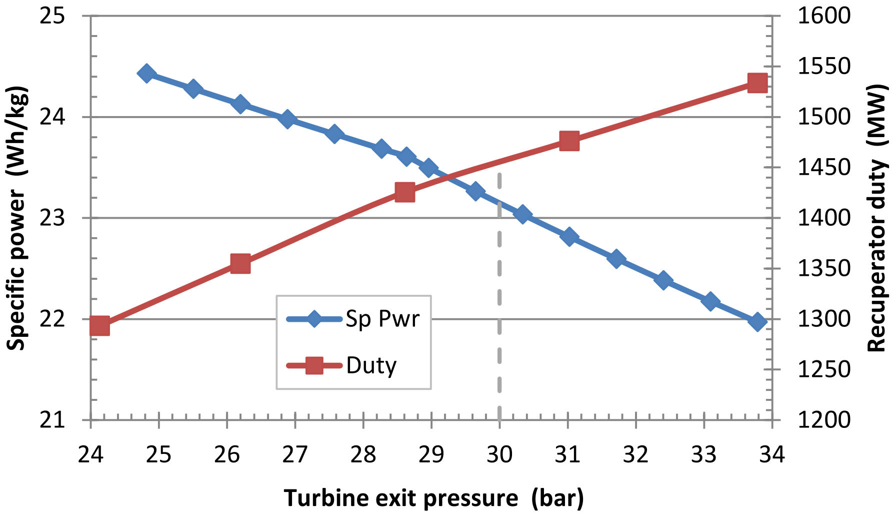
Sensitivity Analyses

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

Sensitivity Analyses (cont.)

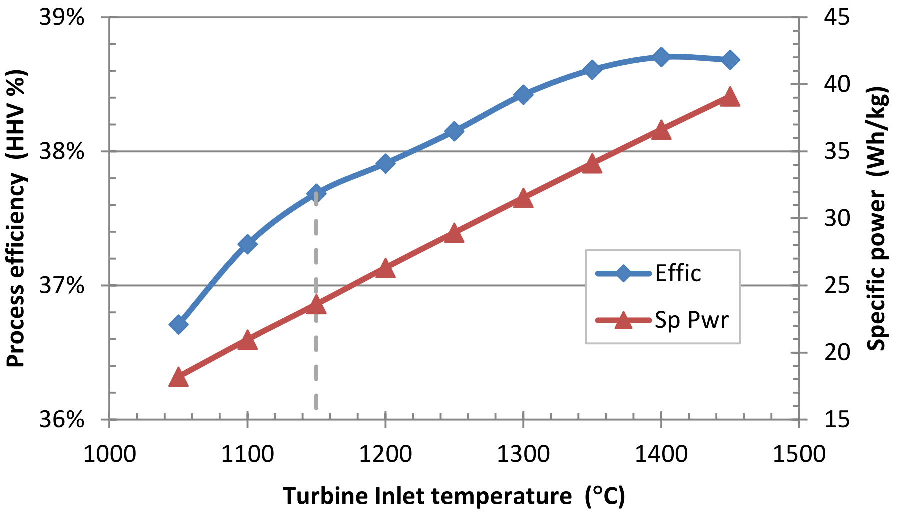
- **For sensitivity to turbine exit pressure, all other parameters kept constant except …**
  – Turbine exit temperature limited to 760 °C
  – Turbine inlet temperature limited to 1149 °C
  – CO_2 purge fraction adjusted to attain limiting turbine inlet or exit temperature
- **Maximum process efficiency 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

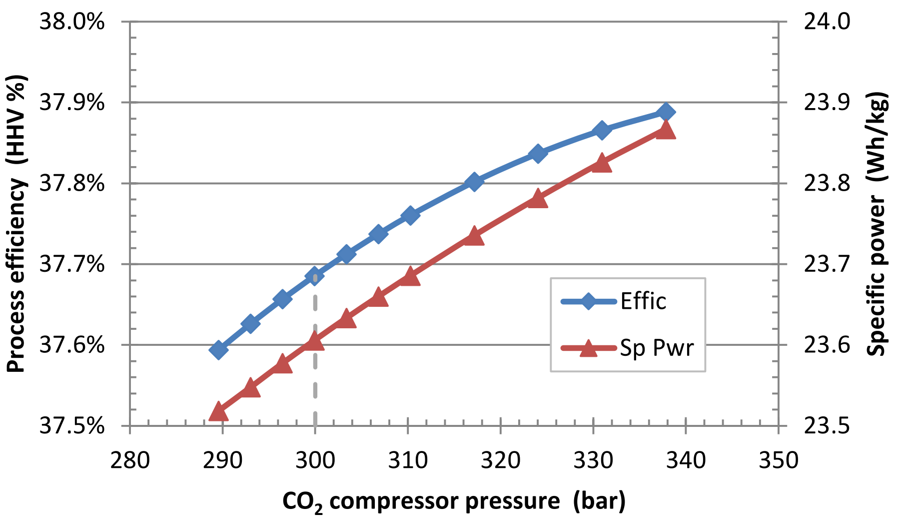




Sensitivity Analyses (cont.)

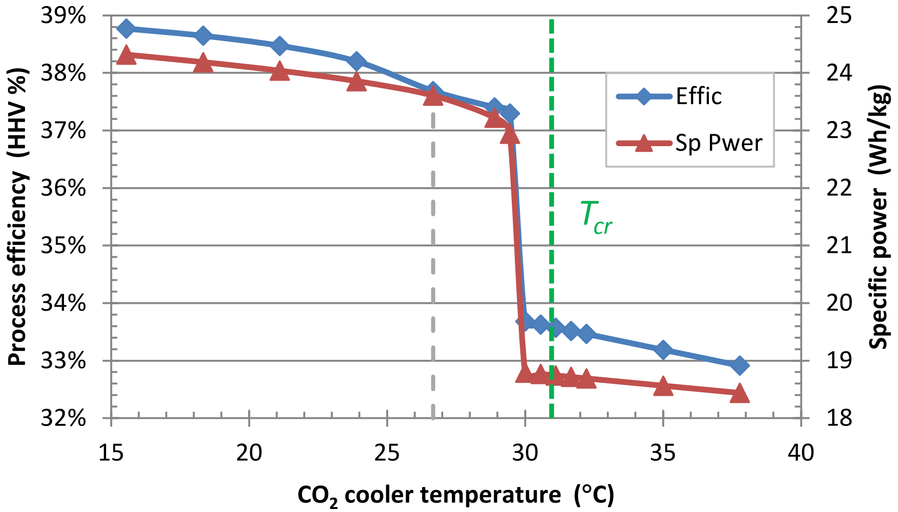
- **Turbine inlet temperature:**
  - Turbine exit pressure adjusted to yield exit temperature of 760 °C
  - Increasing turbine inlet temp.:
    - Increases pressure ratio
    - Increases required fuel and oxidizer, reducing sCO_2 purity
    - Increases specific power
  - Must account for cost of materials and blade cooling
- **Compressor exit pressure:**
  - Turbine exit pressure adjusted to yield maximum efficiency
  - Increasing efficiency and specific power with pressure
  - Impact of pressure on wall thicknesses and cost of expensive alloys must be considered

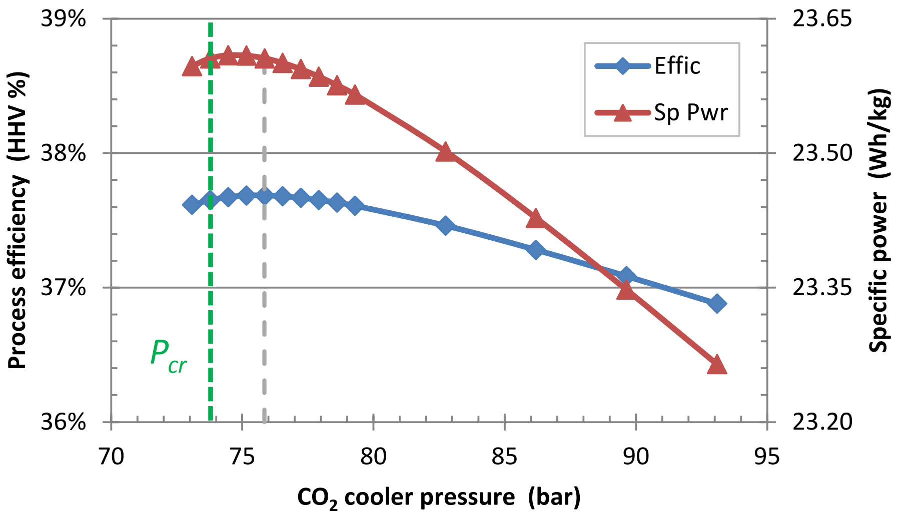




Sensitivity Analyses (cont.)

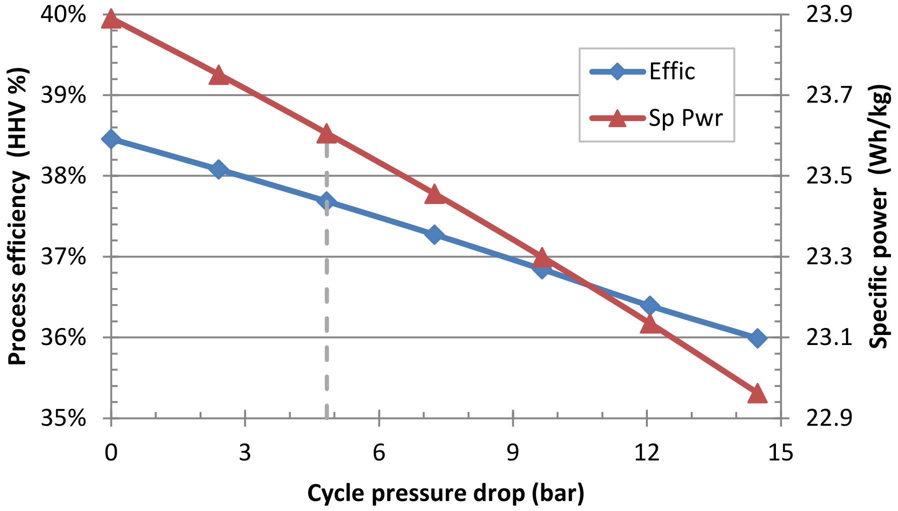
- **CO_2 Cooler Temperature**
  - Demonstrates the benefit of operating in a condensing sCO_2 cycle to reduce compression power requirements
  - Does not account for needed refrigeration at low temperature
- **CO_2 Cooler Pressure**
  - Intermediate pressure between the sCO_2 compressor and pump
  - 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)**

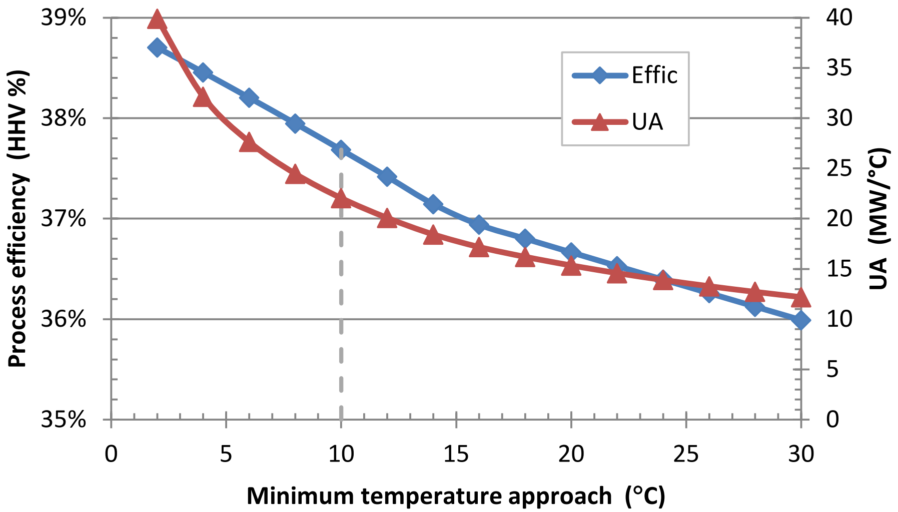




Sensitivity Analyses (cont.)

- **Cycle Pressure Drop**
  - Assumed pressure drop of 4.8 bar is a rough estimate
  - Large reductions in efficiency, lesser reductions in specific power
  - Low pressure drops expected to significantly increase capital cost
- **Minimum 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 to Additional Intercooling

- **In the baseline configuration, final CO_2 compression from 75.8 bar to 300 bar is done in a single stage**
- **A variation of the baseline configuration is evaluated with compression performed in two stages with intercooling to 27 °C**
- **Results in a 0.45 percentage point increase in process efficiency**
  - Due to an 8 percent drop in the sCO_2 cycle compression power required
  - Aggregate cooling duty and compressor power duty both decrease
- **This is an attractive option that will be pursued in future studies**

Parameter	Baseline sCO_2 Cycle	Additional Intercooling
Process efficiency (HHV %)	37.7	38.1
CO_2 cooler duty (MW)	560	559
CO_2 cycle compression power (MW)	181	167
Thermal input to cycle (MW)	1,315	1,314

Conclusions and Future Work

- **Conclusions:**
  - Direct coal-fired sCO_2 cycle developed shows improved performance relative to IGCC reference case

Parameter	IGCC	sCO_2 Cycle	EPRI sCO_2 Cycle*
Net power output (MWe)	497	563	583
Net plant efficiency (HHV %)	31.2	37.7	39.6
Carbon capture fraction (%)	90	98	99
Captured CO_2 purity (mol% CO_2)	99.99	99.44	98.1

  - Capital costs are expected to be lower due to replacement of gas turbine and steam bottoming cycle
  - Sensitivity studies provide guidelines for improving performance and reducing costs
- **Future Work**
  - Improve plant design by incorporating intercooling in the final compression stage
  - Investigate 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

* Case 3 from: *Performance and Economic Evaluation of Supercritical CO2 Power Cycle Coal Gasification Plant.* EPRI, Palo Alto, CA: 2014. 3002003734.

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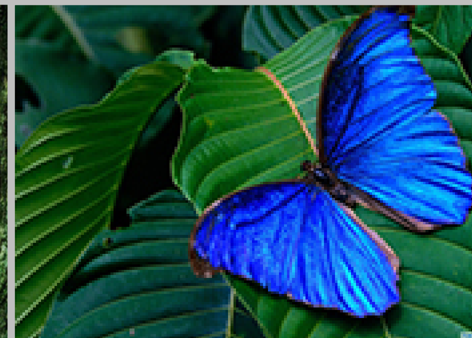
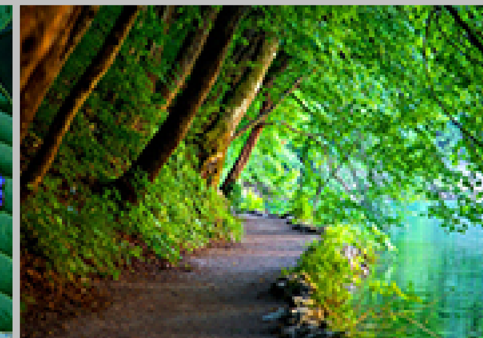

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