Update on the Techno-Economic Viability of AUSC Systems

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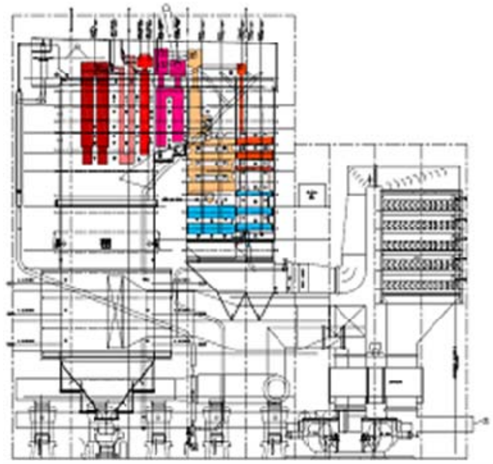
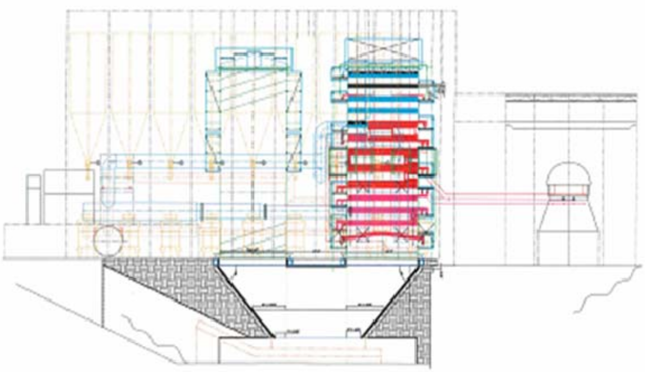


Conventional Boiler



Downdraft Inverted Tower Boiler*

* Figure used with permission from B&W

Objectives

- **Conduct assessments of advanced material-enabled coal-fueled power plants**
  - Advanced ultrasupercritical (AUSC) Rankine-cycle-based pulverized coal (PC) plants
  - Supercritical carbon dioxide (sCO_2) oxy-circulating fluidized bed (CFB) plants
- **Thermodynamic and economic analyses**
  - Analyses follow NETL Quality Guidelines for Energy Systems Studies (QGESS)
  - Cost estimates developed at same detail level as NETL's Cost and Performance Baseline for Fossil Energy Plants report series; in particular, Volume 1, Bituminous Coal and Natural Gas to Electricity (the "Bituminous Baseline")
  - Bituminous Coal (Illinois #6), generic Midwestern location, ISO ambient conditions
  - Estimated emissions of Hg, PM, NOx, and SO_2 are all at or below the applicable regulatory limits at the time of preparation for all cases
  - 2011 $
  - 85% capacity factor
  - CCS cases include transport and storage (T&S) in a saline formation
  - Incorporated results from the literature and in consultation with developers for advanced technologies

Evaluation Basis – PC Plants

Thermodynamic Performance

- **ASPEN Plus models**
  - Based on NETL Bituminous Baseline supercritical PC (SC PC) cases B12A (no CCS) and B12B (with CCS)
  - NETL supercritical steam conditions - 3500 psig/1100°F/1100°F
- **550MW net scale**
- **Reliant upon a notional downdraft inverted tower boiler (B&W)**
- **AUSC conditions for temperature/pressure**
  - T - HP: 1350°F, RH: 1400°F
  - P - HP: 3500, 4250, 5000 psig

Evaluation Basis – PC Plants

Economics

- **Scaling from Bituminous Baseline SC PC cases B12A and B12B for commercial and post-combustion capture technology sections**
- **Components requiring advanced materials and/or novel designs**
  - Notional downdraft inverted tower boiler
    - Information/discussions with B&W
    - Previous NETL study
  - Main and reheat steam leads
    - Use of aforementioned boiler reduces lead lengths from ~450 ft found in conventional boiler designs to ~160 ft
    - Assumed $40/lb for Inconel 740H pipe
  - Steam turbine generator (STG) and accessories
    - AUSC Consortium data (EPRI/GE)

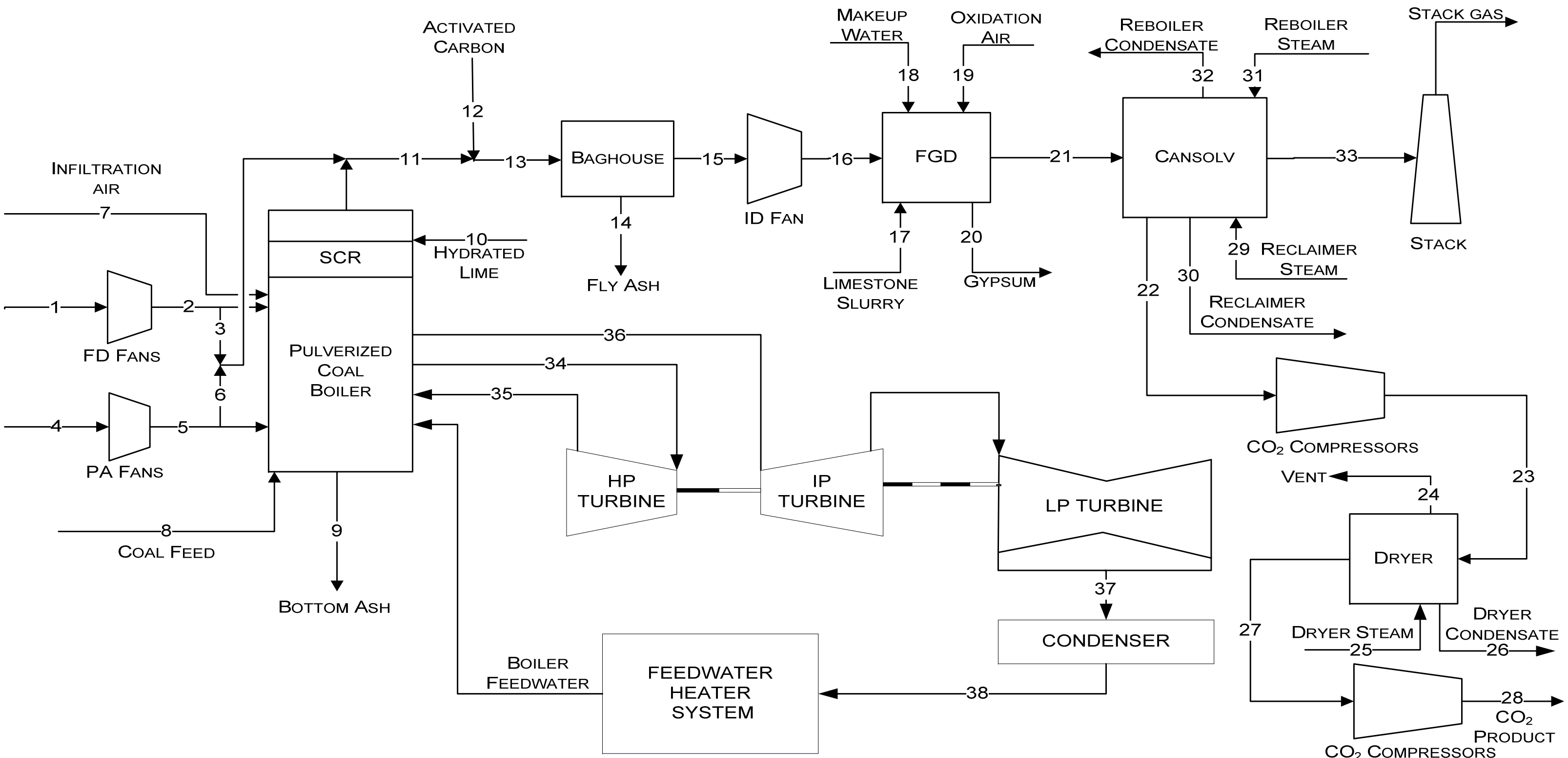
Case Matrix – PC Plants

Case	Unit Cycle	Steam Cycle, psig/°F/°F	Boiler Technology	Oxidant	Sulfur Removal/ Recovery	PM Control	NOx Control	CO_2 Separation [A]
Case 1	PC	3500/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB w/OFA and SCR	N/A
Case 2	PC	3500/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB w/OFA and SCR	Cansolv
Case 3	PC	4250/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB w/OFA and SCR	N/A
Case 4	PC	4250/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB w/OFA and SCR	Cansolv
Case 5	PC	5000/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB and SCR	N/A
Case 6	PC	5000/1350/1400	Conceptual Inverted Tower	Air	Wet FGD/ Gypsum	Baghouse	LNB w/OFA and SCR	Cansolv

[A] All capture cases have a nominal 90 percent (90%) removal rate based on the total feedstock minus unburned carbon in ash. The rate of CO_2 capture from the flue gas in the Shell Cansolv systems varies. An explanation for the difference is provided in Report Section 2.3.2. All cases sequester the CO_2 offsite.

Block Flow Diagram – PC Plants

Study Cases 2, 4, and 6 (w/ CCS)



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

Source: NETL

Results – PC Plants

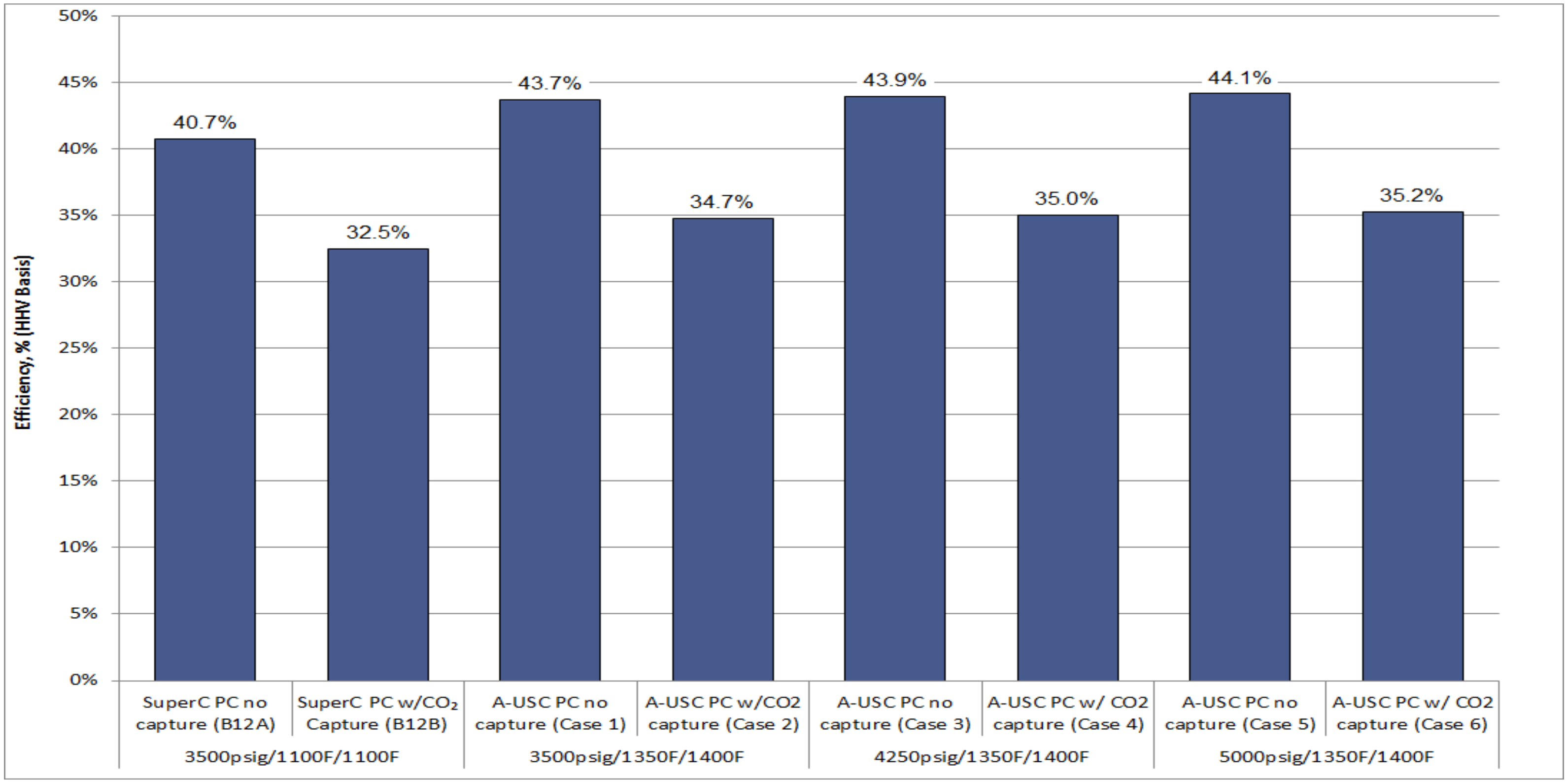
Thermodynamic Performance and Emissions

	Pulverized Coal Boiler							
	PC Supercritical		PC A-USC					
Case Name	B12A	B12B	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
PERFORMANCE								
Gross Power Output (MWe)	580	642	578	635	578	634	578	633
Auxiliary Power Requirement (MWe)	30	91	27	85	27	84	27	84
Net Power Output (MWe)	550	550	550	550	550	550	550	550
Coal Flow rate (lb/hr)	395,053	495,578	368,475	463,058	366,459	458,873	364,825	456,109
HHV Thermal Input (kW_t)	1,350,672	1,694,366	1,259,804	1,583,179	1,252,911	1,568,872	1,247,323	1,559,420
Net Plant HHV Efficiency (%)	40.7%	32.5%	43.7%	34.7%	43.9%	35.0%	44.1%	35.2%
Net Plant HHV Heat Rate (Btu/kWh)	8,379	10,508	7,814	9,826	7,769	9,741	7,732	9,683
Raw Water Withdrawal, gpm	5,105	7,882	4,508	7,124	4,461	7,025	4,422	6,960
Process Water Discharge, gpm	1,059	1,813	930	1,638	919	1,615	911	1,600
Raw Water Consumption, gpm	4,045	6,069	3,578	5,486	3,541	5,410	3,511	5,360
CO_2 Capture Rate (%)	0%	90%	0%	90%	0%	90%	0%	90%
CO_2 Emissions (lb/MMBtu)	204	20	204	20	204	20	204	20
CO_2 Emissions (lb/MWh-gross)	1,618	183	1,515	173	1,506	172	1,500	171
CO_2 Emissions (lb/MWh-net)	1,705	214	1,590	200	1,581	198	1,574	197

Note: The average annual CO_2 emissions limit for new coal plants under Section 111(b) of the Clean Air Act is 1,400 lb CO_2/MWh-gross. To accommodate start-ups, shut-downs, and part-load operation, the design emissions level will have to be some amount less than this limit.

Results – PC Plants

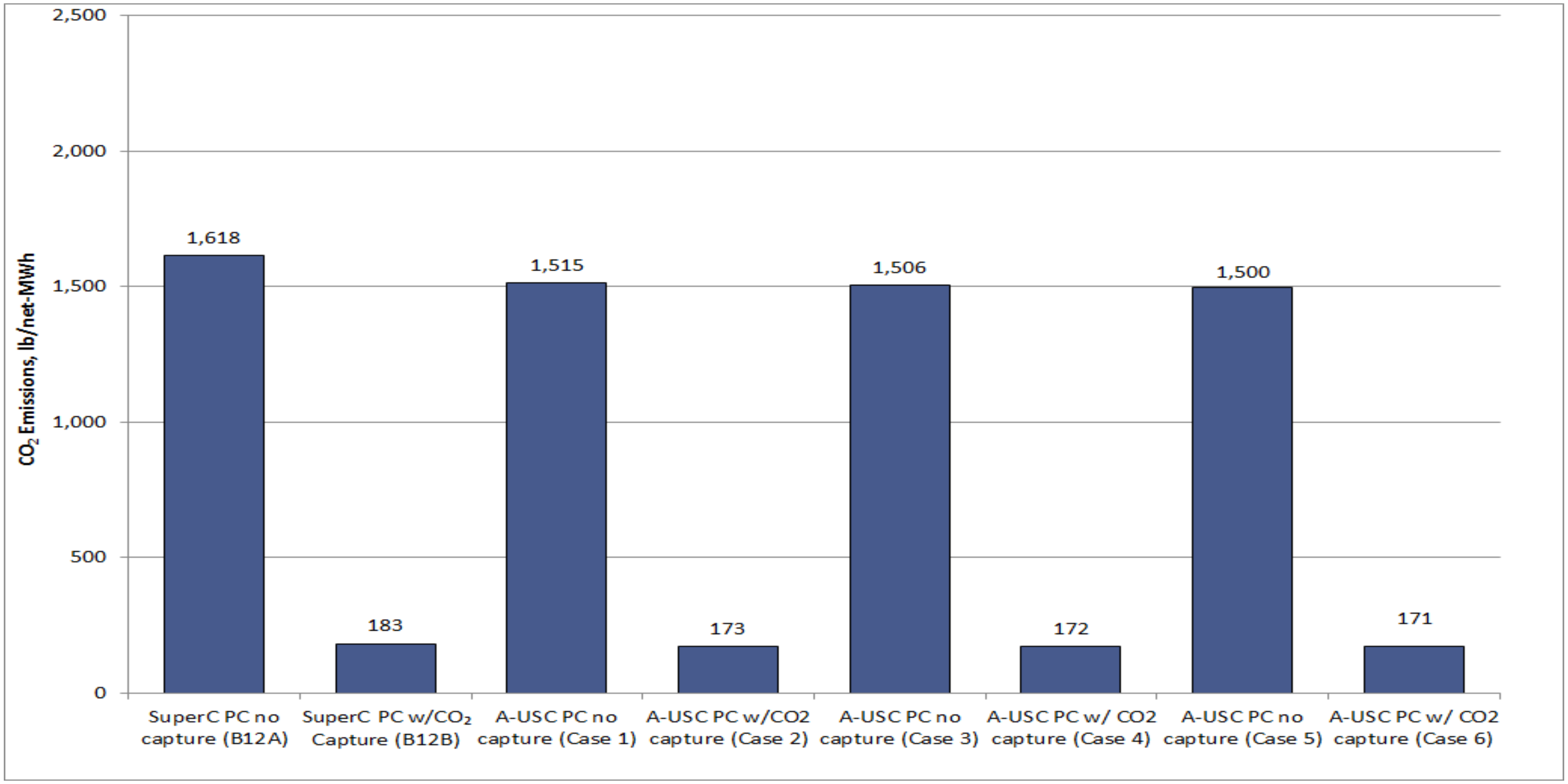
Efficiency



Source: NETL

Results – PC Plants

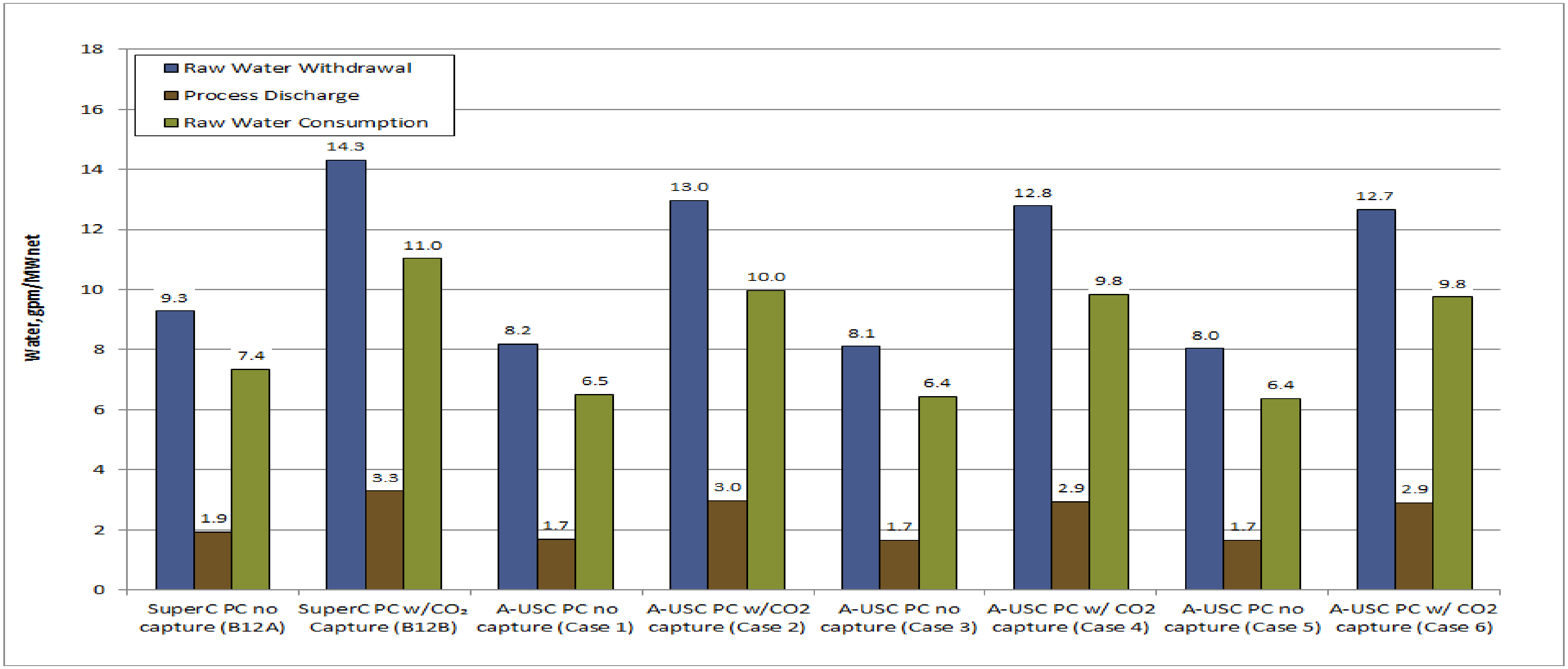
CO_2 Emissions



Source: NETL

Results – PC Plants

Raw Water Withdrawal and Consumption



Source: NETL

Results – PC Plants

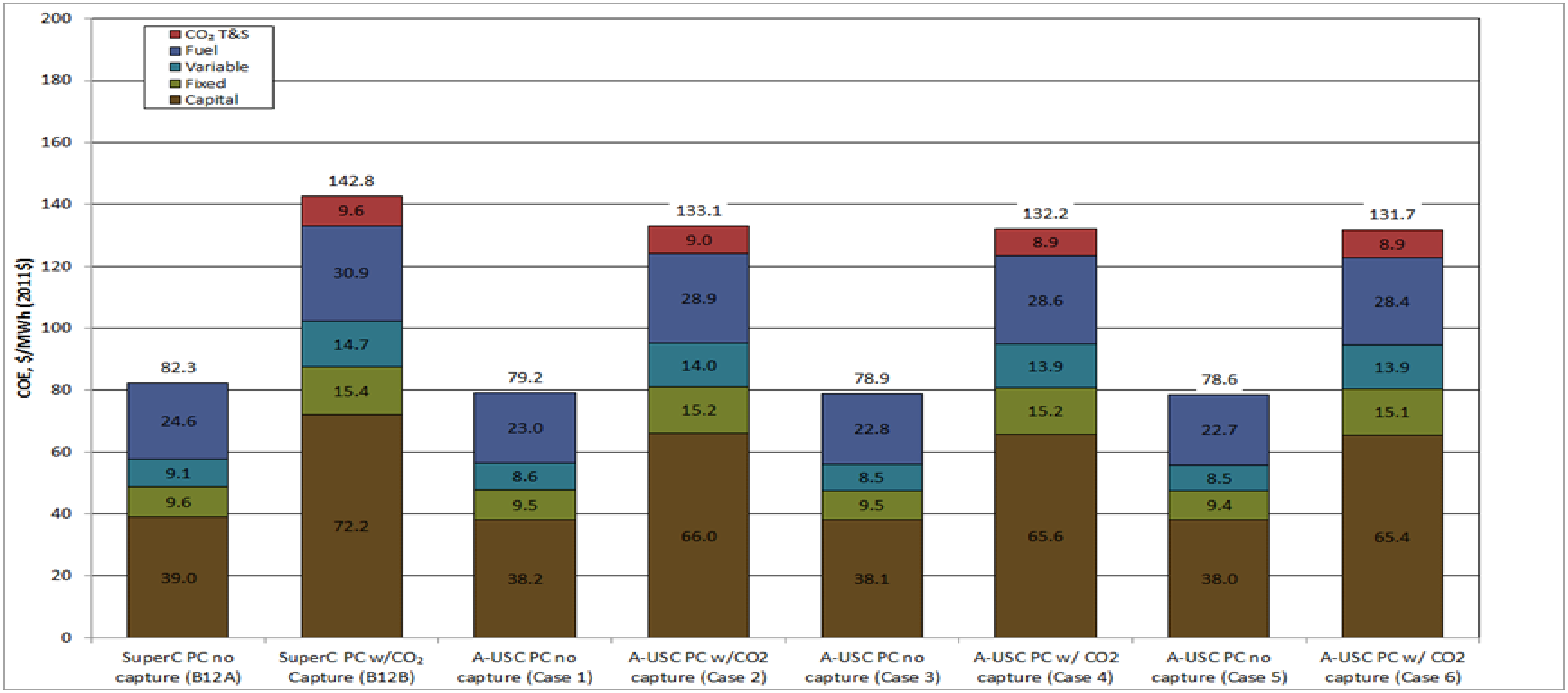
Economics

	PC Supercritical		PC A-USC					
Case Name	B12A	B12B	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
COST								
Total Plant Cost (2011$/kW)	2,026	3,524	1,986	3,447	1,977	3,429	1,972	3,417
Bare Erected Cost	1,646	2,716	1,614	2,660	1,607	2,646	1,603	2,636
Home Office Expenses	165	263	161	258	161	256	160	256
Project Contingency	216	430	210	419	209	417	209	416
Process Contingency	0	115	0	111	0	110	0	110
Total Overnight Cost (2011$MM)	1,379	2,384	1,350	2,329	1,345	2,316	1,341	2,308
Total Overnight Cost (2011$/kW)	2,507	4,333	2,455	4,236	2,444	4,214	2,437	4,199
Owner's Costs	480	809	469	789	467	785	465	782
Total As-Spent Cost (2011$/kW)	2,842	4,940	2,784	4,829	2,772	4,804	2,764	4,787
COE ($/MWh) (excluding T&S)	82.3	133.2	79.2	124.1	78.9	123.3	78.6	122.8
Capital Costs	39.0	72.2	38.2	66.0	38.1	65.6	38.0	65.4
Fixed Costs	9.6	15.4	9.5	15.2	9.5	15.2	9.4	15.1
Variable Costs	9.1	14.7	8.6	14.0	8.5	13.9	8.5	13.9
Fuel Costs	24.6	30.9	23.0	28.9	22.8	28.6	22.7	28.4
COE ($/MWh) (including T&S)	82.3	142.8	79.2	133.1	78.9	132.2	78.6	131.7
CO_2 T&S Costs	0.0	9.6	0.0	9.0	0.0	8.9	0.0	8.9
CO_2 Captured Cost (excluding T&S), $/tonne	N/A	58.2	N/A	51.1	N/A	50.7	N/A	50.4
CO_2 Avoided Cost (including T&S), $/tonne	N/A	89.4	N/A	74.3	N/A	73.0	N/A	72.2

*Cases without capture use conventional financing; all others use high-risk financial assumptions consistent with NETL's "QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance

Results – PC Plants

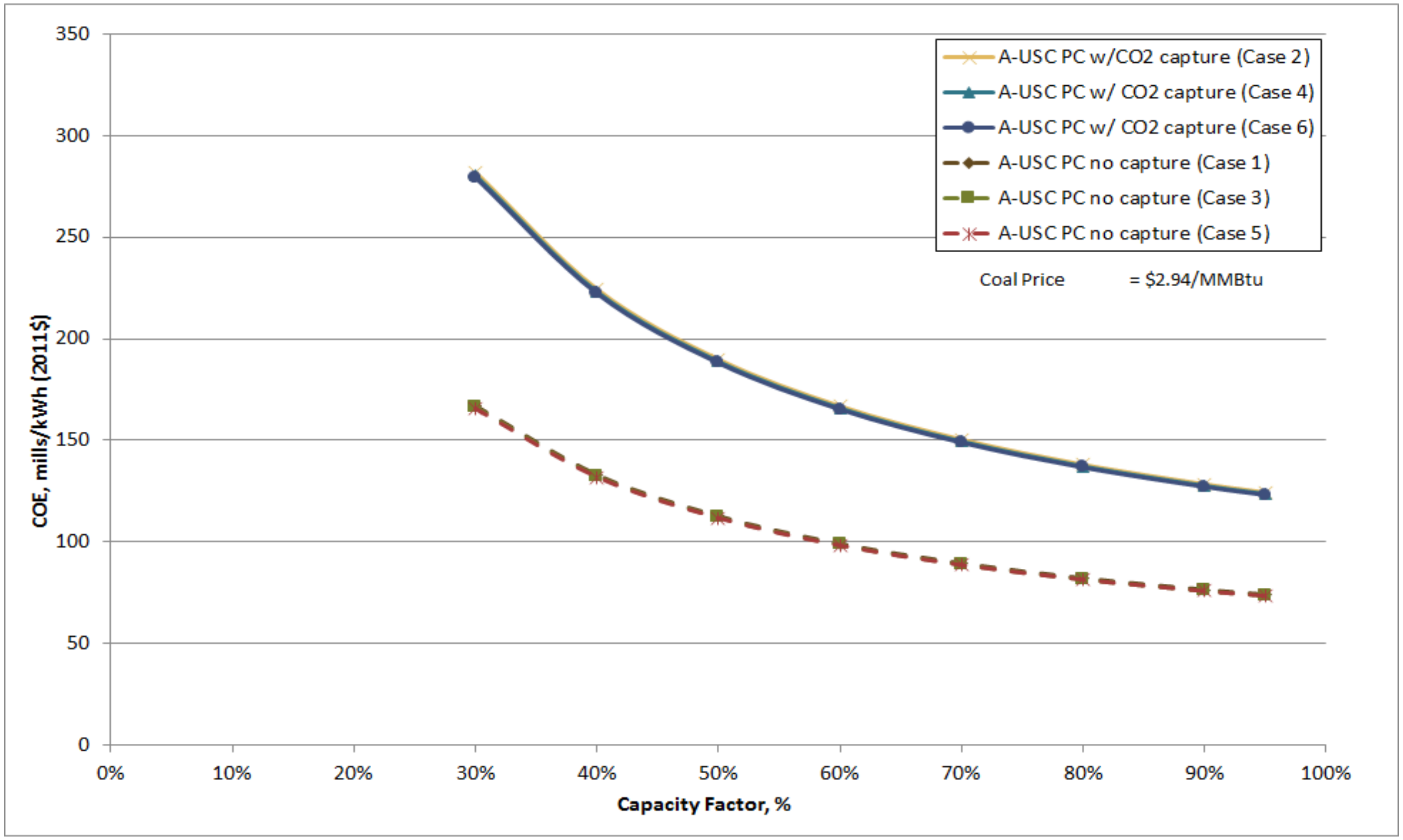
Cost of Electricity (COE)



Source: NETL

Results – PC Plants

Sensitivity – Capacity Factor

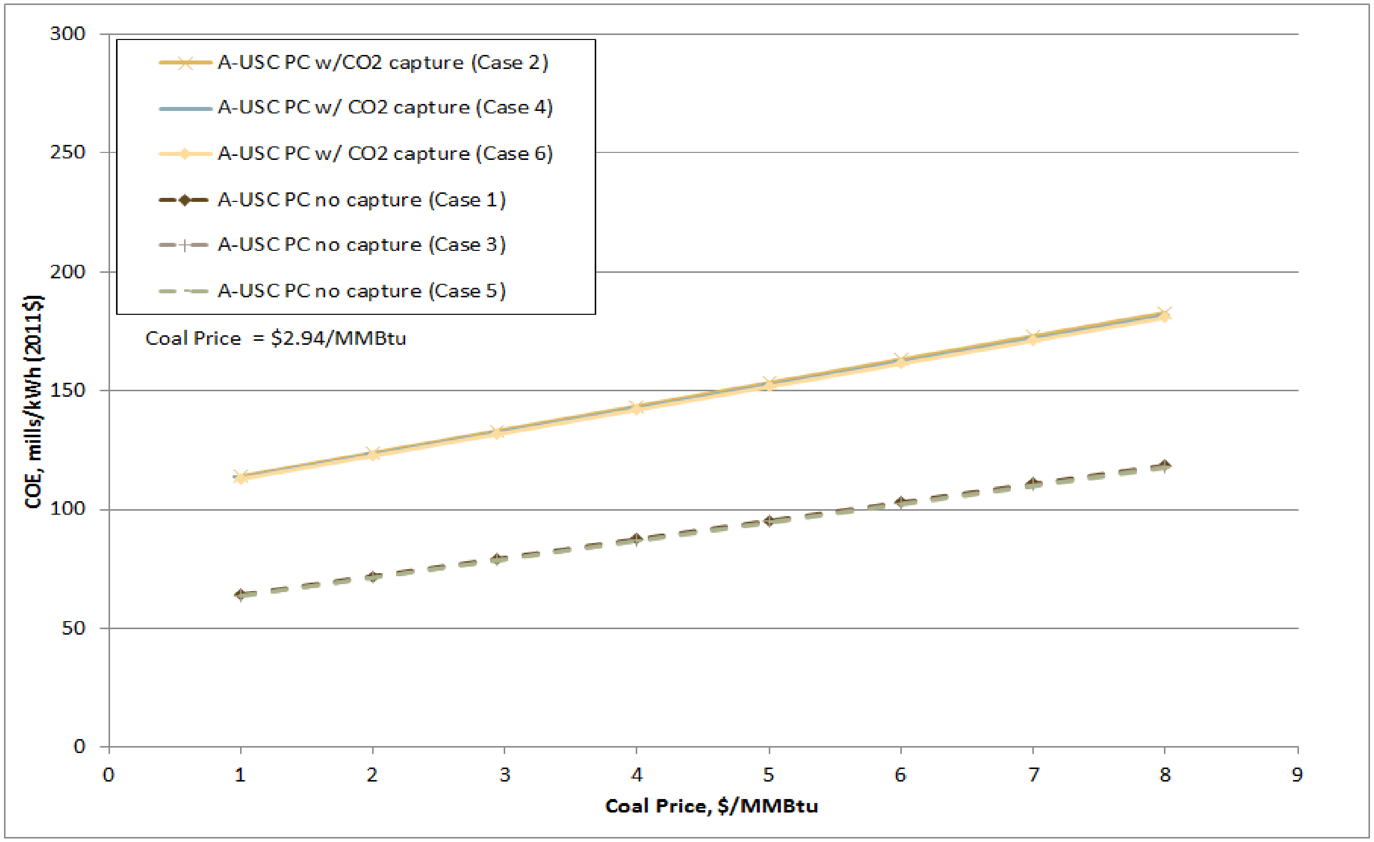


CO_2 capture cases include T&S

Source: NETL

Results – PC Plants

Sensitivity – Coal Price

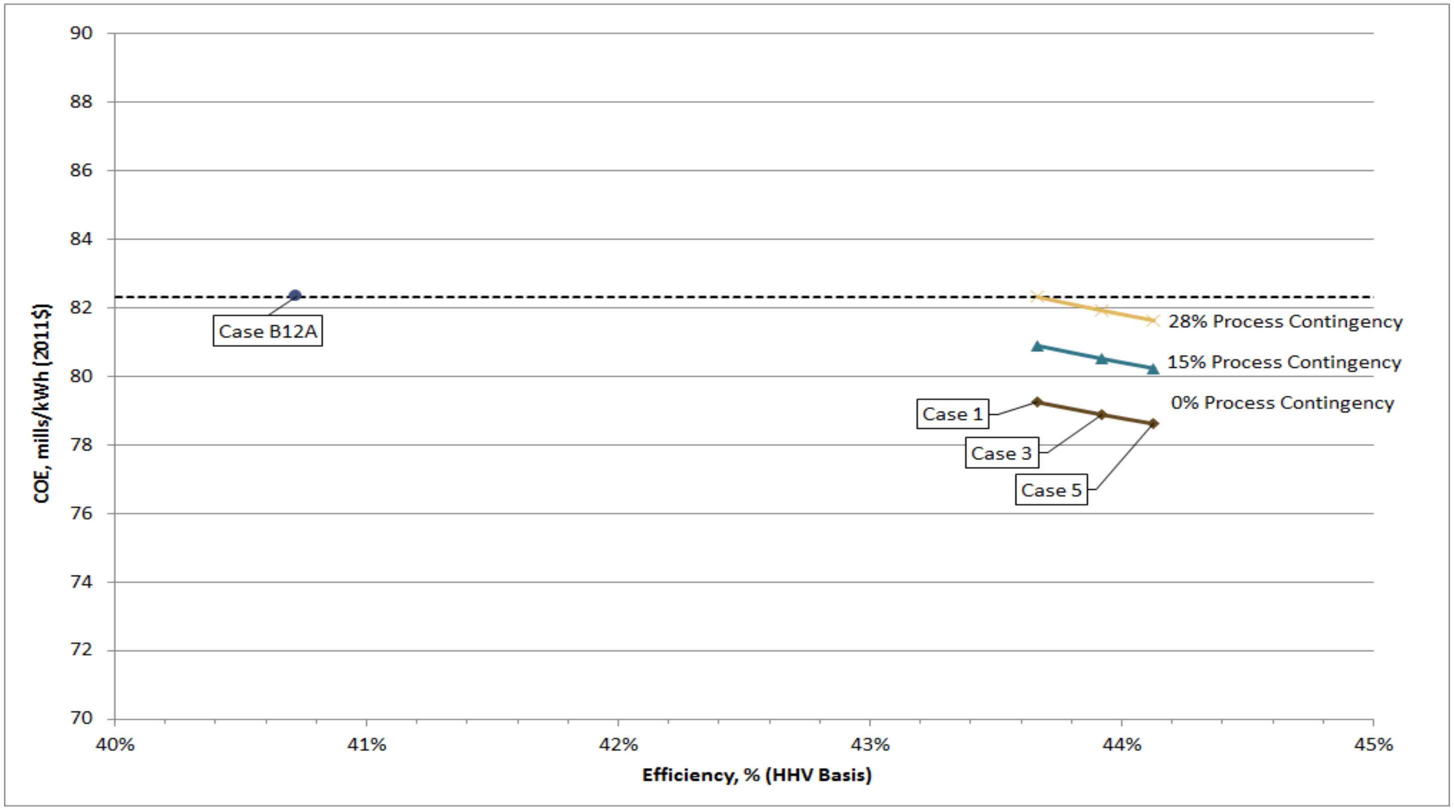


CO_2 capture cases include T&S

Source: NETL

Results – PC Plants

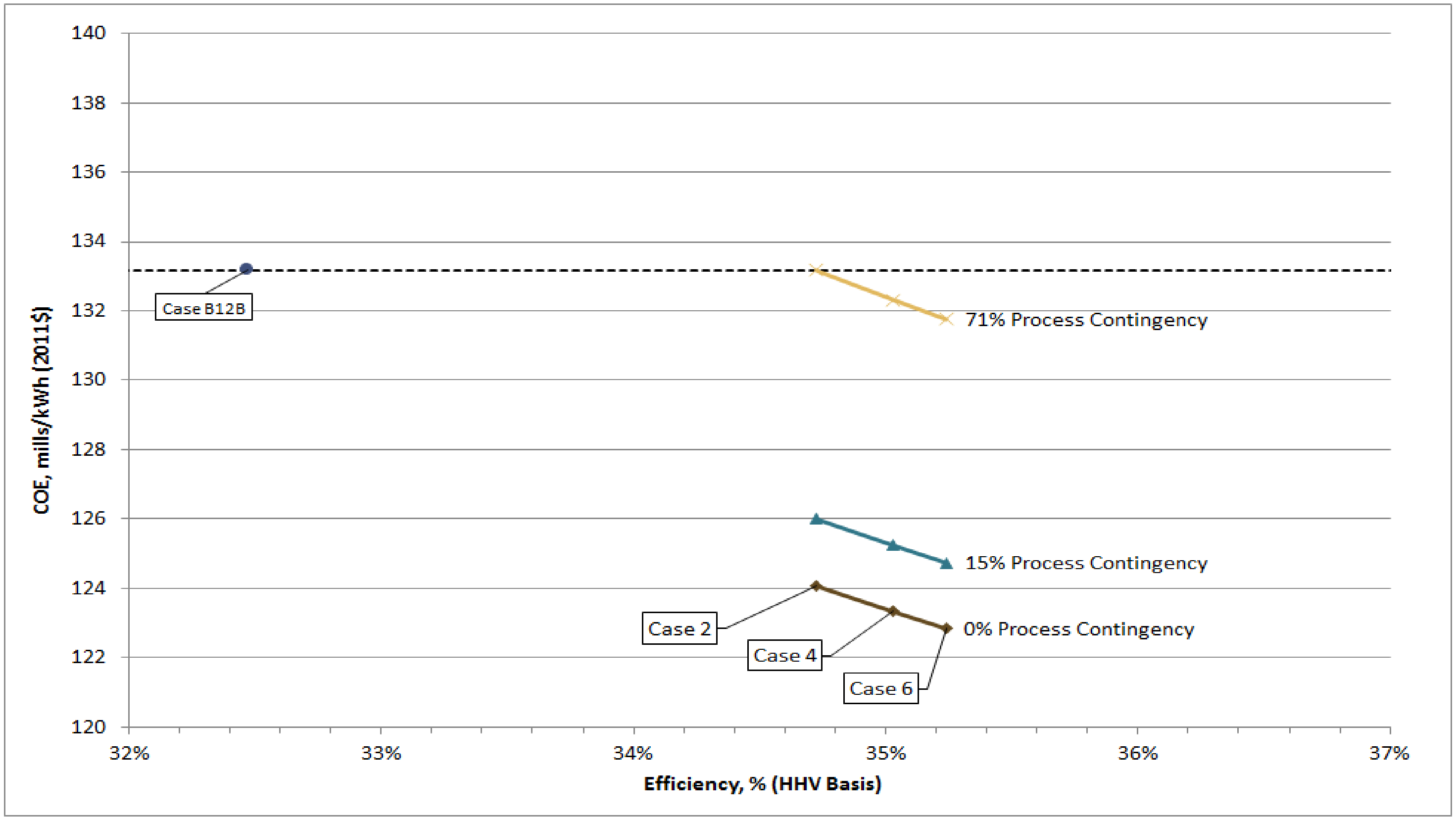
Sensitivity – Boiler Cost (w/o CCS)



Source: NETL

Results – PC Plants

Sensitivity – Boiler Cost (w/ CCS)



Source: NETL

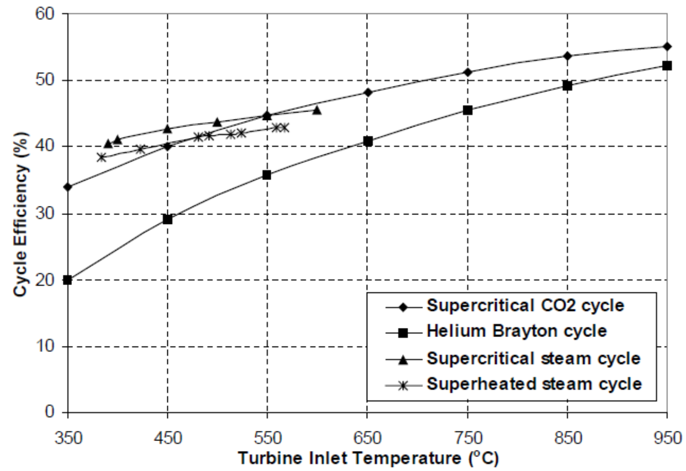
Results – PC Plants

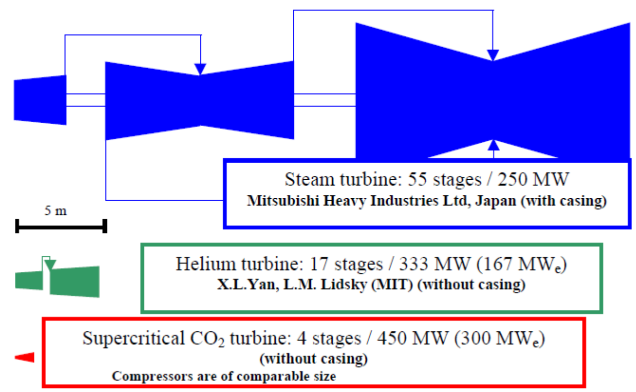
Summary

- **PC plants without CCS gain 3.0% points; with CCS, 2.2% points**
  - SC (3500 psig/1100°F/1100°F) to AUSC (3500 psig/1350°F/1400°F)
  - Small gains with incremental increases in main steam pressure
- **PC plants without CCS show a 3.8% decrease in COE; with CCS, 6.8%**
  - SC (3500 psig/1100°F/1100°F) to AUSC (3500 psig/1350°F/1400°F)
  - Small decreases with incremental increases in main steam pressure
- **Primary uncertainty is downdraft inverted tower boiler**
  - Cost estimation, particularly as configured for AUSC steam conditions
- **Multiple approaches taken to estimate cost of steam leads**
  - Very small COE effect

Overview – Indirect sCO_2 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.

Evaluation Basis – sCO_2 Plants

Thermodynamic Performance

- **ASPEN Plus models**
  - Based on NETL atmospheric pressure oxy-CFB with a supercritical Rankine cycle (B22F)
  - Evaluated an atmospheric pressure oxy-CFB with an AUSC Rankine cycle (B24F)
  - Series of cases with Rankine cycle replaced with an indirect sCO2 cycle (closed recompression Brayton cycle)
- **AUSC conditions for Rankine cycle temperature/pressure**
  - T - HP: 1400 °F, RH: 1400 °F
  - P - HP: 3500 psig
- **AUSC conditions for sCO_2 temperature/pressure**
  - T - HP: 1400 °F, RH: 1400 °F
  - P - HP: 5000 psig
- **sCO_2 analyses included base, reheat, intercooling, and reheat + intercooling cases**

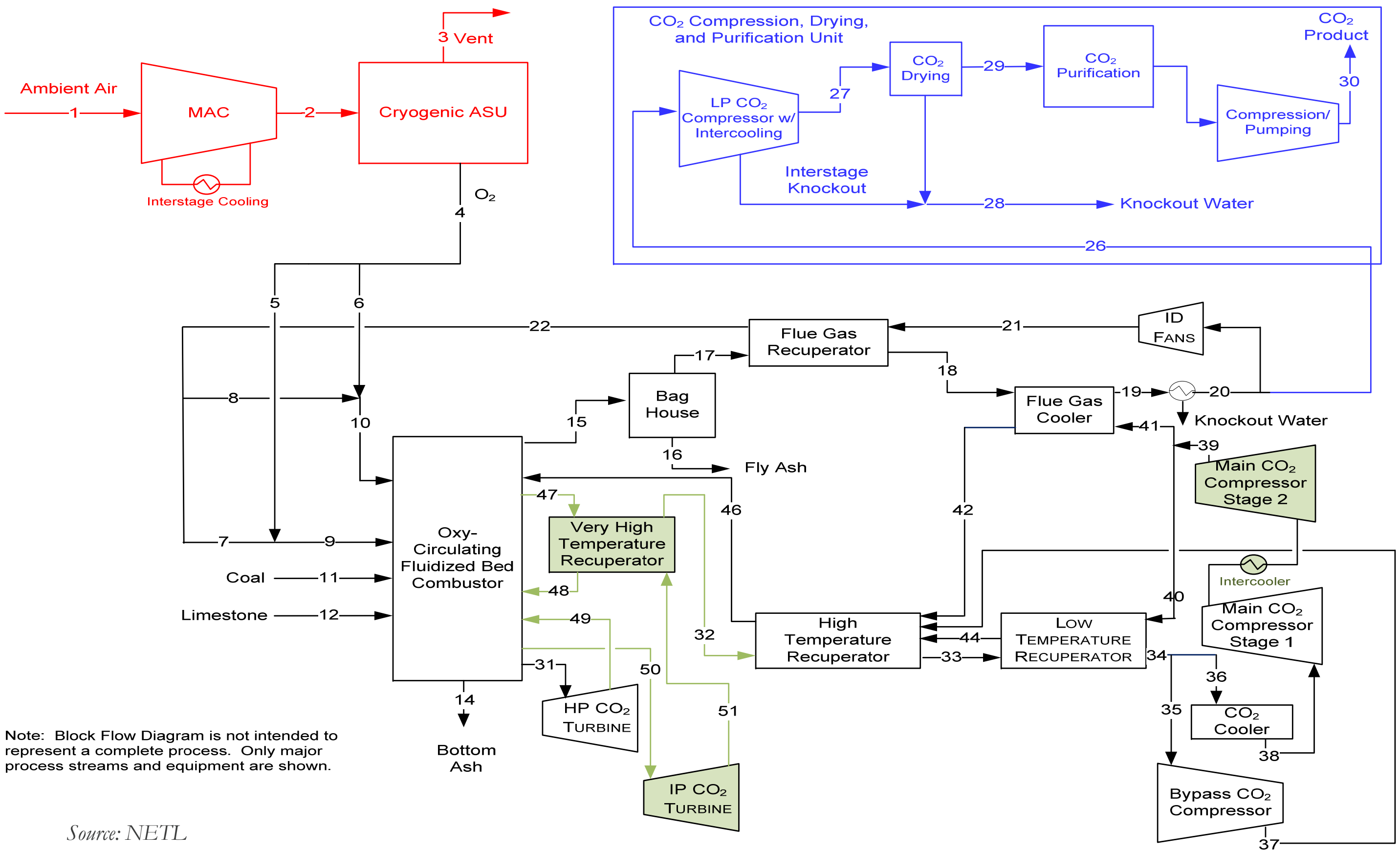
Evaluation Basis – sCO_2 Plants

Economics

- **Scaling from atmospheric oxy-CFB with a SC Rankine cycle for commercial technology sections, and previously-presented AUSC PC study**
- **SCO_2 components requiring advanced materials and/or novel designs**
  - CFB
    - Modification and scaling of previous NETL study
  - Main and reheat sCO_2 leads
    - ~150 ft in length, Assumed $40/lb for Inconel 740H pipe
  - sCO_2 turbine
    - Le Moullec paper, with adjustments
  - High- and low-temperature sCO_2 recuperators
    - Aerojet Rocketdyne, with adjustments
  - Main and bypass sCO_2 compressors
    - MAN Turbo

Block Flow Diagram – sCO2 Plants

With Reheat and Intercooling



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

Source: NETL

Case Matrix – sCO_2 Plants

Case (°F)	Reheat	Inter-cooling	Boiler Technology	Cycle Conditions (psig/°F/°F)	Sulfur Capture / Removal*	PM control	CO_2 Separation / Gas Cleanup
Base (1150)	No	No	Oxy-CFB	5000/1150	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
Reheat (1150)	Yes	No	Oxy-CFB	5000/1150/1150	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
InterCooling (1150)	No	Yes	Oxy-CFB	5000/1150	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
Reheat/InterCooling (1150)	Yes	Yes	Oxy-CFB	5000/1150/1150	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
Base (1400)	No	No	Oxy-CFB	5000/1400	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
Reheat (1400)	Yes	No	Oxy-CFB	5000/1400/1400	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
InterCooling (1400)	No	Yes	Oxy-CFB	5000/1400	Limestone injection / ash	Baghouse	Auto Refrigerated CPU
Reheat/InterCooling) (1400)	Yes	Yes	Oxy-CFB	5000/1400/1400	Limestone injection / ash	Baghouse	Auto Refrigerated CPU

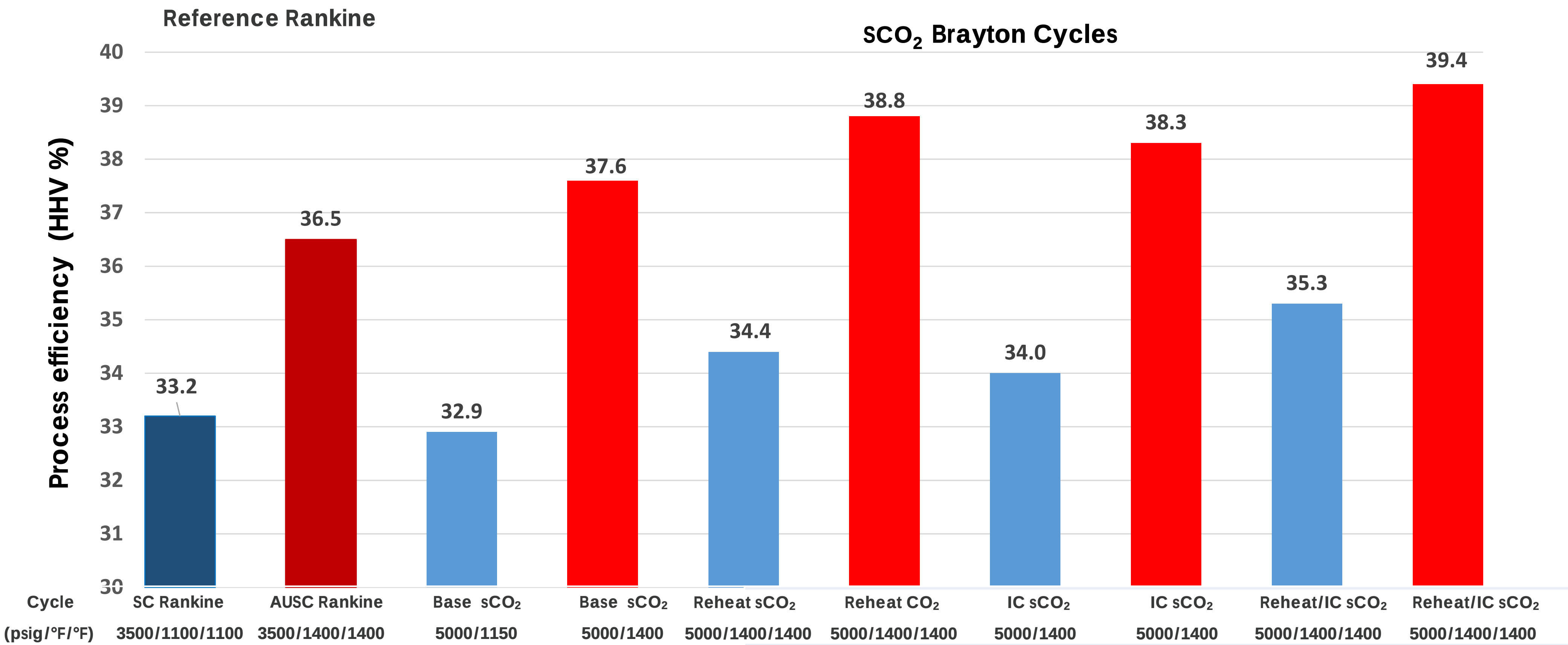
* Sulfur removal is primarily in the cyclone bottom ash and baghouse fly ash, Emissions (lb/MWhgross) were set at SOx =1.0, NOx =0.7, PM=0.09, and Hg = 0.000003

Results – sCO_2 Plants

Thermodynamic Performance and Emissions

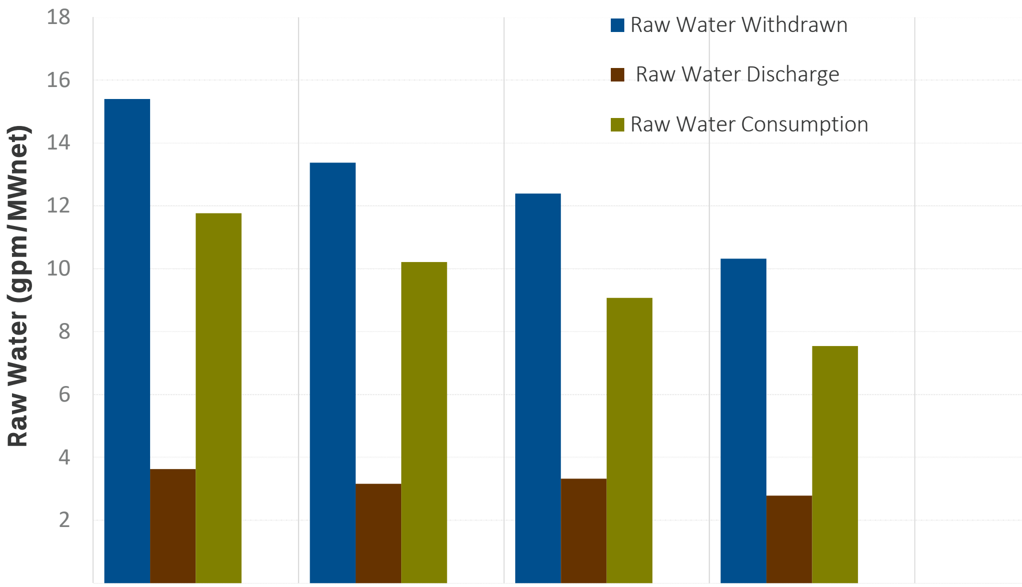
Parameter	Reference SC Rankine (B22F)	Reference AUSC Rankine (B24F)	sCO2 Rht/IC (T=1150 °F)	sCO2 Rht/IC (T=1400 °F)
CFB Coal Flow Rate (lb/hr)	483,994	441,293	456,032	408,616
Limestone Flow Rate (lb/hr)	116,535	106,123	109,898	98,472
Oxygen Flow Rate (lb/hr)	1,034,064	942,849	975,627	874,198
sCO_2 Flow Rate (lb/hr)	---	---	37,234,900	29,863,300
Steam to HP Turbine (lb/hr)	4,403,776	3,375,905	---	---
Net Plant Efficiency (HHV %)	33.23	36.45	35.27	39.37
HHV Heat Rate (Btu/kWh)	10,267	9,876	9,673	8,668
sCO_2 Power Cycle Efficiency (%)	---	---	49.49	53.89
sCO_2 Cycle Heat Rate (Btu/kWh)	---	---	6,894	6,332
Steam Power Cycle Efficiency (%)	48.27	51.8	---	---
Steam Cycle Heat Rate (Btu/kWh)	7069	6,582	---	---
Coal Thermal Input (MMBtu/hr)	5,646	5,148	5,320	4,767
Power Cycle Thermal Input (MMBtu/hr)	5,109	4,653	4,932	4,417
Fractional Thermal Input to Power Cycle	0.905	0.904	0.927	0.927
Raw Water Withdrawal (gpm)	8,466	7,355	6,816	5,676
Raw Water Discharge (gpm)	1,994	1,738	1,826	1,529
Raw Water Consumption (gpm)	6,472	5,617	4,990	4,147
Power Summary				
Steam Turbine Power Output	722,836	707,328	0	0
sCO_2 Cycle Power Output	0	0	715,305	697,587
Gross Power Output	722,836	707,328	715,305	697,587
Total Auxiliary Power Load	172,851	157,308	165,308	147,597
Net Power Output	549,985	550,020	549,997	549,990
CO_2 Emissions (lb/MWh-gross)	119	111	53	47
CO_2 Emissions (lb/MWh-net)	156	142	69	60

Results – sCO_2 Plants - Efficiency



Results – sCO_2 Plants

Raw Water: Withdrawal, Discharge and Consumption



Cycle	SC Rankine	AUSC Rankine	Base sCO_2	Base sCO_2
(psig/°F/°F)	3500/1100/1100	3500/1400/1400	5000/1150	5000/1400

Cycle	Reference SC Rankine	Reference AUSC Rankine	sCO2 Rht/IC (T=1150 °F)	sCO2 Rht/IC (T=1400 °F)
gpm				
Raw Water Withdrawal	8,466	7,355	6,816	5,676
Raw Water Discharge	1,994	1,738	1,826	1,529
Raw Water Consumption	6,472	5,617	4,990	4,147
Net Power (MW)	550	550	550	550
gpm/MWnet				
Raw Water Withdrawal	15.4	13.4	12.4	10.3
Raw Water Discharge	3.6	3.2	3.3	2.8
Raw Water Consumption	11.8	10.2	9.1	7.5

Results – sCO_2 Plants

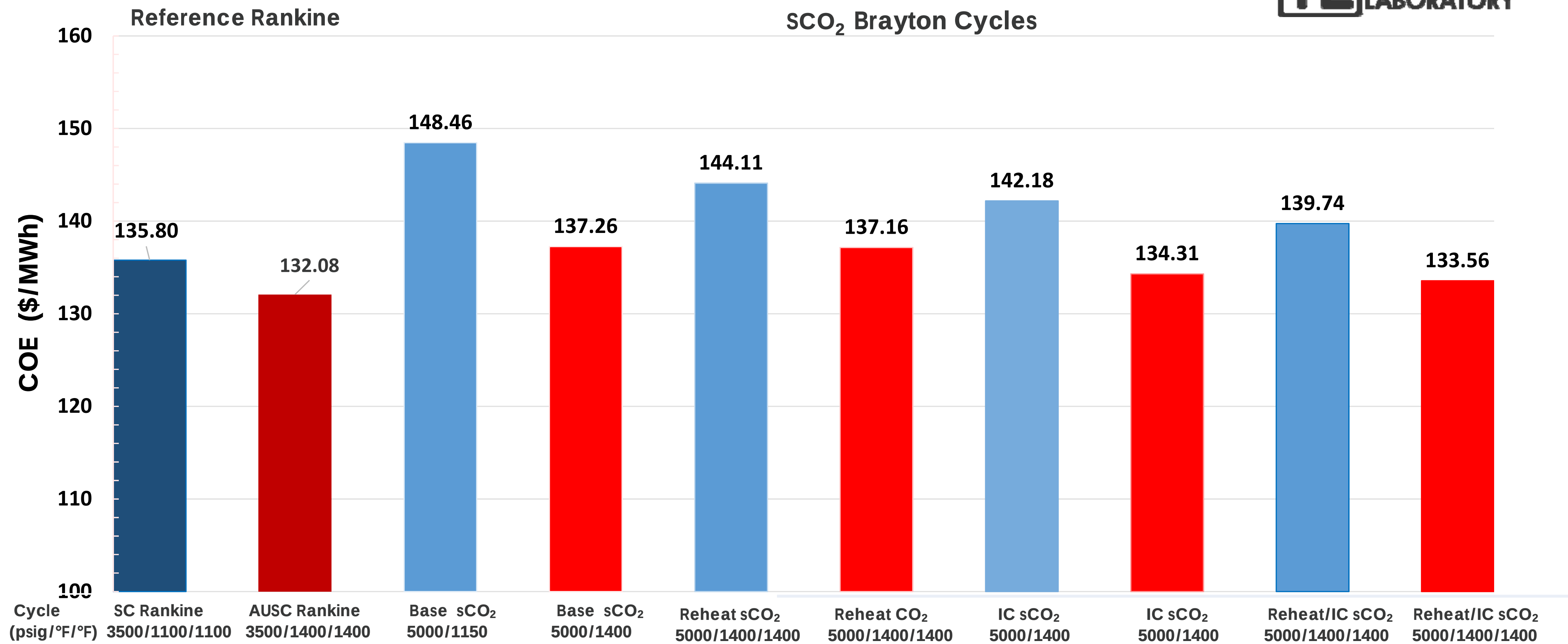
Economics

Cycle	OXY-CFB Rankine		OXY-CFB sCO2 (Brayton)	
Case Name	B22F	B24F	sCO2 Reheat/IC (T=1150 °F)	sCO2 Reheat/IC (T=1400 °F)
COST				
Total Plant Cost (2011$/kW)	3,337	3,363	3800	3601
Bare Erected Cost	2,666	2,695	3017	2864
Home Office Expenses	245	247	282	268
Project Contingency	371	369	443	417
Process Contingency	55	51	58	52
Total Overnight Cost (2011$MM)	2,255	2,270	2561.35	2561
Total Overnight Cost (2011$/kW)	4,101	4,127	4657	4418
Owner's Costs	501	505		
Total As-Spent Cost (2011$/kW)	4,675	4,705	5309	5036
COE ($/MWh) (excluding T&S)	127.2	124.2	139.3	129.2
Capital Costs	68.3	68.7	77.6	73.6
Fixed Costs	14.8	14.9	16.6	15.8
Variable Costs	13.8	12.9	14.8	13.2
Fuel Costs	30.2	27.5	30.5	26.7
COE ($/MWh) (including T&S)	135.8	132.1	148.5	137.3
CO_2 T&S Costs	8.7	7.9	9.1	8.0

Source: NETL

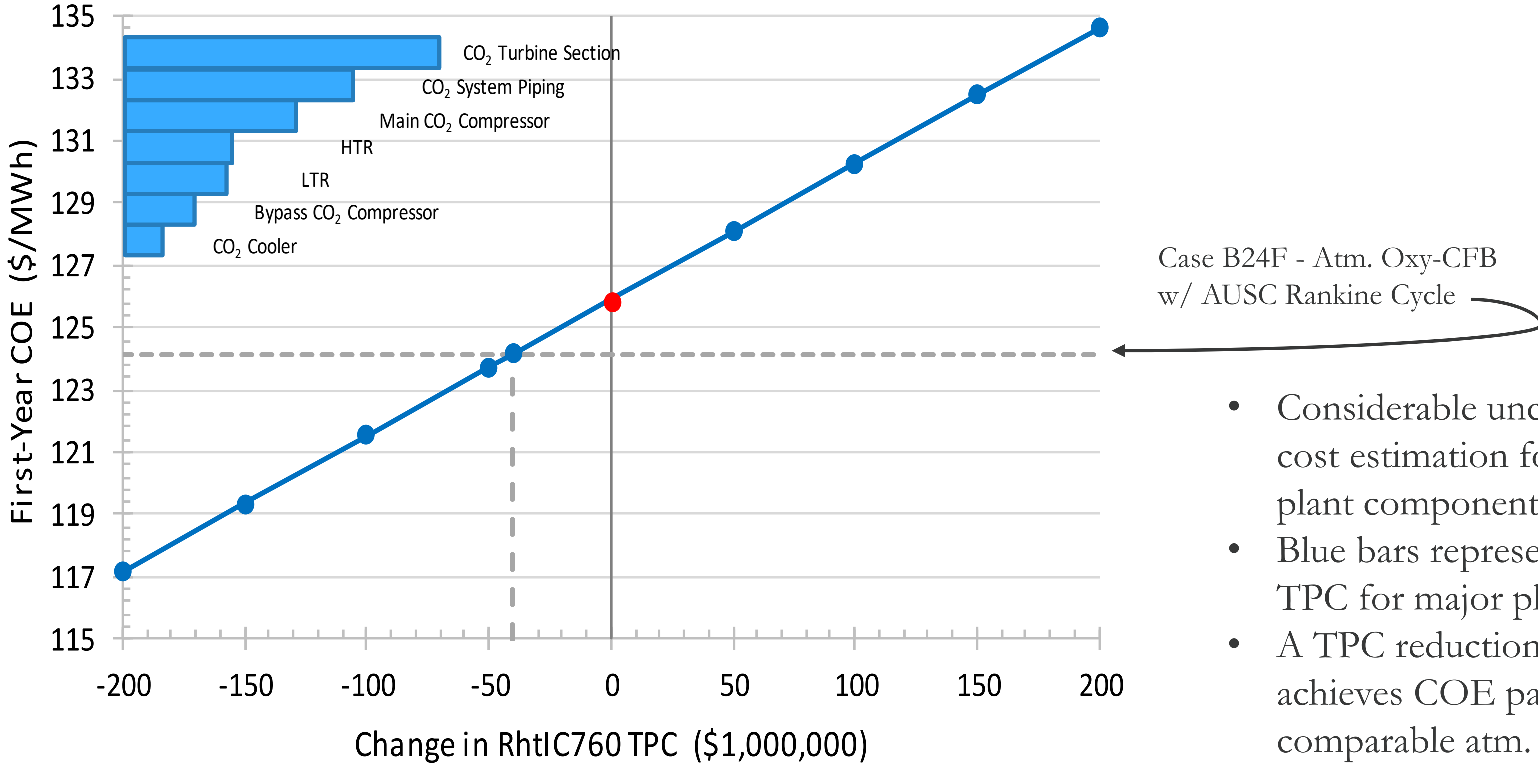
Results – sCO$_2$ Plants

Cost of Electricity (with T&S)



Results – sCO_2 Plants

Sensitivity – TPC for RhtIC760 Case



- Considerable uncertainty with capital cost estimation for certain sCO_2 plant components.
- Blue bars represent the estimated TPC for major plant components.
- A TPC reduction of ~$40MM achieves COE parity with a comparable atm. Oxy-CFB AUSC Rankine plant.

COE excludes T&S

Source: NETL

Results – sCO_2 Plants

Summary

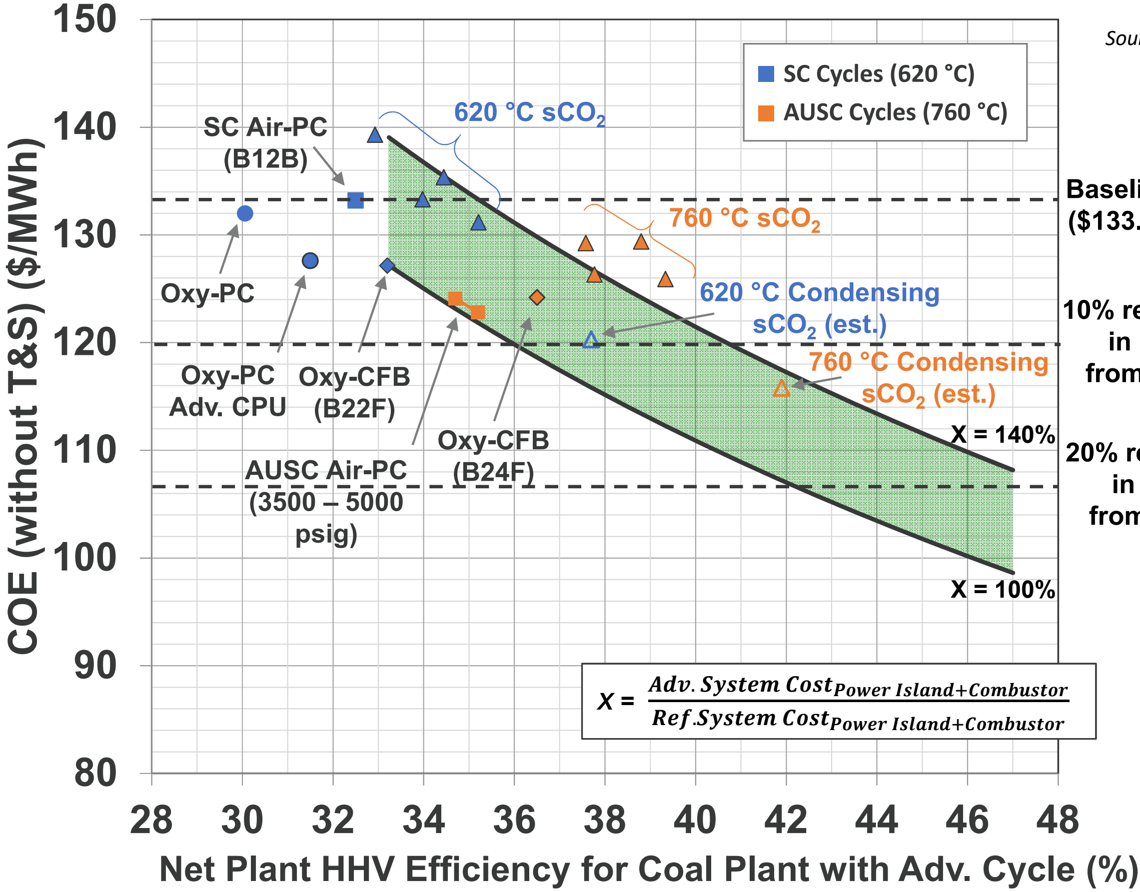
- **The AUSC sCO_2 cycle atm. Oxy-CFB plant with reheat and intercooling provides a 2.9% point improvement over the comparable AUSC Rankine cycle atm. Oxy-CFB plant**
  - 39.4% HHV vs. 36.5% HHV
- **However, COE is equivalent between these cases**
  - $124/MWh (Rankine) vs. $126/MWh ($sCO_2$)
  - Higher sCO_2 COE primarily due to 8-12x sCO_2 mass flow relative to steam (primary and reheat leads)
  - High- and low-temperature recuperators, and multi-stage sCO_2 compressors (vs. feedwater pumps in a Rankine cycle) also contribute
- **Alternative sCO2 cycle configurations are under development**
- **Large uncertainty in commercial-scale sCO_2 component costs warrant further study**

Cost and Efficiency Summary

Steam Rankine and Indirect sCO_2 cycles with CCS

- Reference: Supercritical Oxy-combustion CFB with Auto-refrigerated CPU (Case B22F)
  - \$0/tonne CO_2 Revenue
  - 550 MWe
- COE reductions are relative to an air-fired, supercritical PC coal plant with CCS (Case B12B)
- Ongoing work assessing condensing CO_2 cycles

Source: NETL



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