Integration of Indirect-Fired Supercritical CO_2 Power Cycles with Coal-Based Heaters

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Overview

- Design and cost 550-MWe coal plant with CO_2 capture and storage (CCS) by combining oxy-combustion with an indirect-fired, supercritical CO_2 (sCO_2) Brayton power cycle and compare the benefits against conventional coal plants with CCS
- In addition, a similar exercise was done for a smaller-scale (90 MWe), air-fired coal plant without CCS
- Six test cases were developed for the study, varying:
  - Net power out: 550 MWe (oxy-fired) and 90 MWe (air-fired)
  - Oxy-combustion technologies: atmospheric pressure oxy-pulverized coal (PC) and chemical looping combustion (CLC)
  - Turbine inlet temperatures: 593°C and 730°C

Presentation will focus on economics

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Test Case Parameters

Case	Net Power, MWe	Coal	Combustion Technology	Base Case/Test Case Turbine Inlet conditions	Base Case Reference
1	550	PRB	Oxy/PC	Base: 593°C / 24.1 MPa Test: 593°C / 24.1 MPa	1
2	550	PRB	Oxy/PC	Base: 730°C / 27.6 MPa Test: 730°C / 27.6 MPa	1
3	550	Illinois Basin	CLC	Base: 593°C / 24.1 MPa Test: 593°C / 24.1 MPa	2
4	550	Illinois Basin	CLC	Base: 730°C / 27.6 MPa Test: 730°C / 27.6 MPa	2
5	90	PRB	Air/PC	Base: 538°C / 10.6 MPa Test: 593°C / 24.1 MPa	3
6	90	PRB	Air/PC	Base: 538°C / 10.6 MPa Test: 730°C / 27.6 MPa	3

References:

1. *Cost and Performance of Low-Rank Pulverized Coal Oxycombustion Energy Plants: Final Report.* DOE/NETL-401/093010. September 2010.
2. *Alstom's Chemical Looping Combustion Technology with CO_2 Capture for New and Retrofit Coal-Fired Power Plants.* Task 2 Final Report, DOE/NETL Cooperative Agreement No. DE-FE0009484. June 2013.
3. B&W internal project files.

Apples-to-apples comparison to existing steam-Rankine cycle base cases

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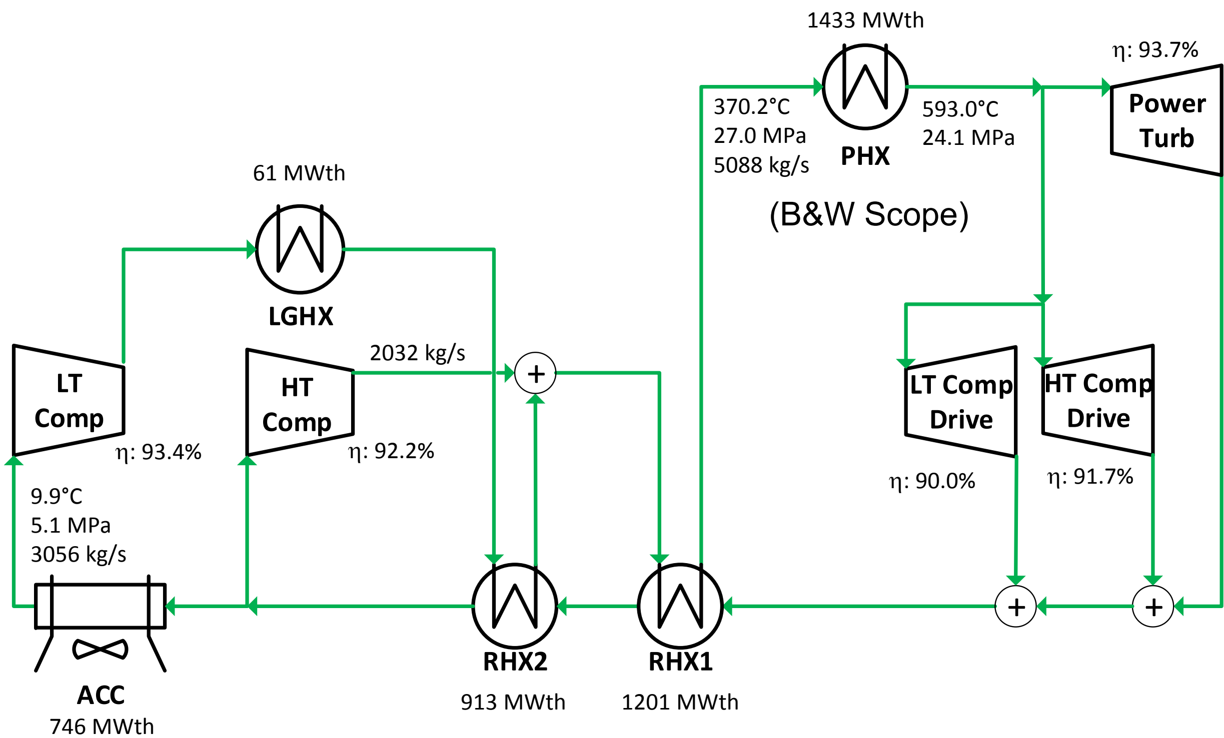
sCO_2 Power Island Design

- All cases use recompression, closed sCO_2 Brayton cycles. Test Cases 1 and 2 add low-grade heat recovery.
- Fired heater (PHX)
  - Pressure drop (dP) and heater efficiency from B&W/GE
  - Minimum approach enforced at each primary heat addition point (27.8°C)
- Turbomachinery efficiencies provided by Doosan and Siemens
- Costs of recuperators (RHX) and air-cooled condenser (ACC) were tracked for “reasonable” design based on:
  - Diminishing cost vs. performance
  - Simplified architecture



Test Case 1 sCO_2 Power Island

Several other cycle types were reviewed (e.g., cascade)

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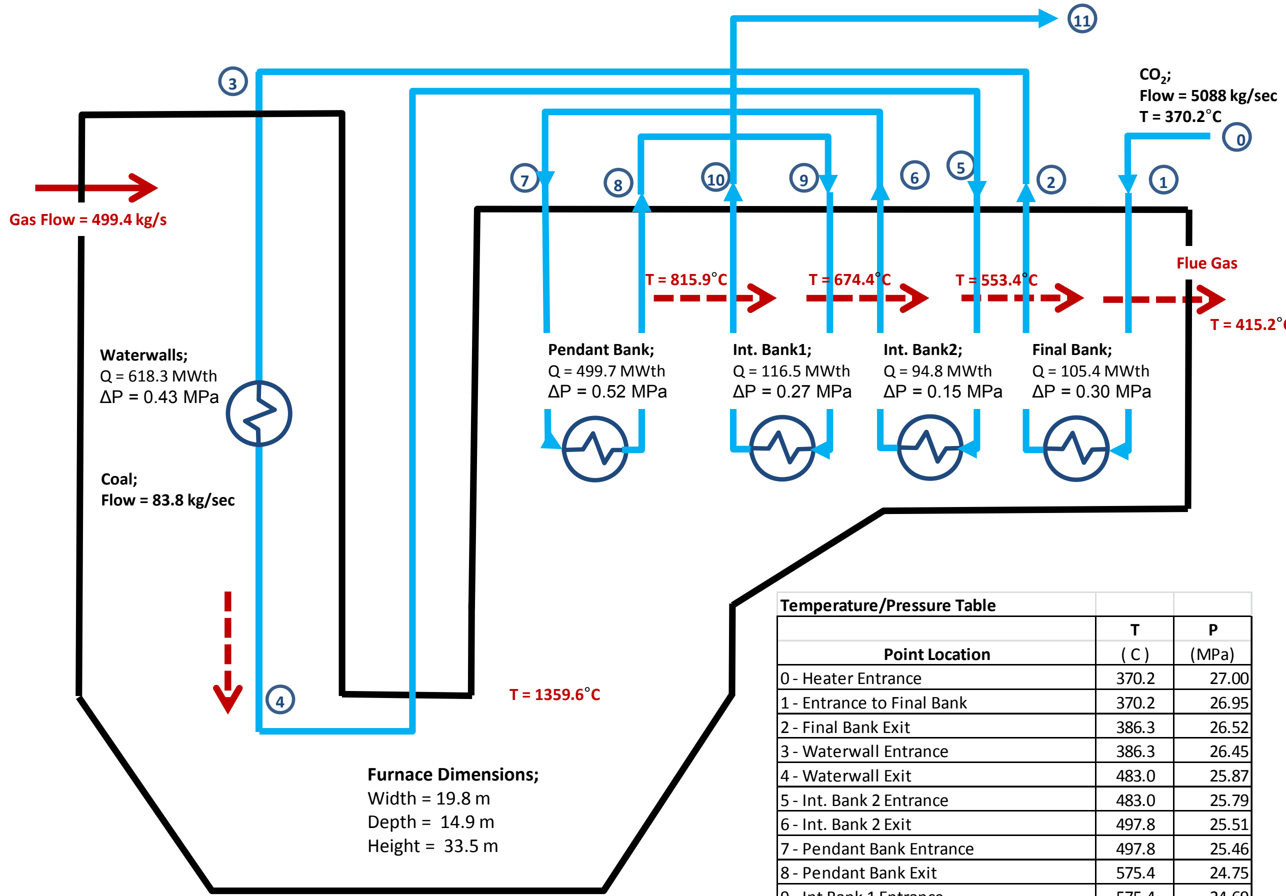
Test Cases 1, 2, 5, and 6 Fired-Heater Design

- B&W completed the design of four (4) PC-fired heater concepts: Test Cases 1 and 2 (oxy) and 5 and 6 (air)
- Inverted heater configuration
  - Reduces pipe lengths to/ from equipment and from convection banks to platen and furnace tube arrays
- To reduce dP, fired heaters are larger with more tubes
- Due to high CO_2 flow rates, even in Test Case 2, nickel alloys were required



Test Case 1 Fired Heater

Temperature/Pressure Table		
Point Location	T (C)	P (MPa)
0 - Heater Entrance	370.2	27.00
1 - Entrance to Final Bank	370.2	26.95
2 - Final Bank Exit	386.3	26.52
3 - Waterwall Entrance	386.3	26.45
4 - Waterwall Exit	483.0	25.87
5 - Int. Bank 2 Entrance	483.0	25.79
6 - Int. Bank 2 Exit	497.8	25.51
7 - Pendant Bank Entrance	497.8	25.46
8 - Pendant Bank Exit	575.4	24.75
9 - Int Bank 1 Entrance	575.4	24.69
10 - Int Bank 1 Exit	593.0	24.26
11 - Heater Exit (to Turbine)	593.0	24.19

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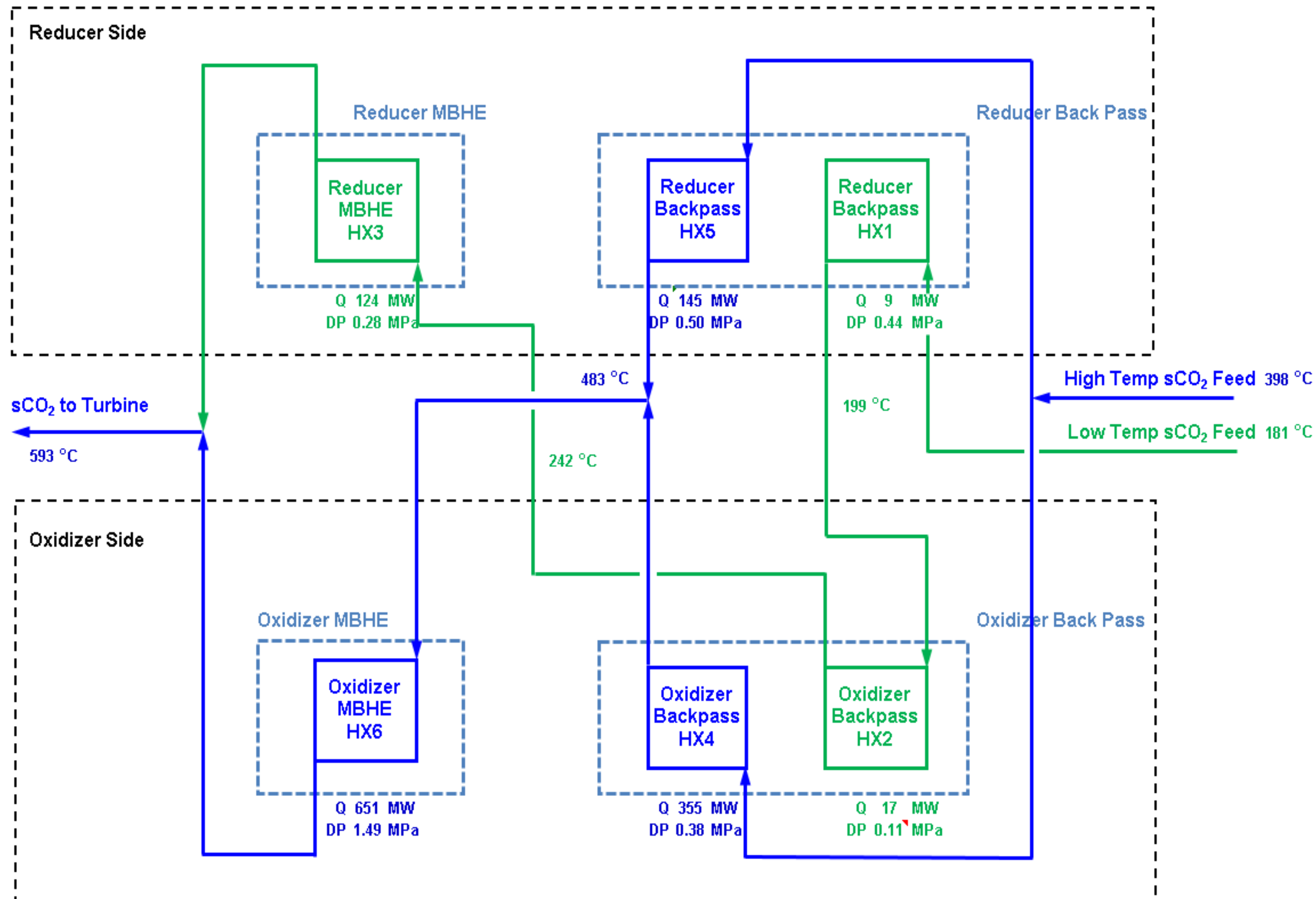
Test Cases 3 and 4 Fired-Heater Design

- GE completed the design of 2 CLC fired-heater concepts: Test Cases 3 and 4
- Impacts on boiler design for manageable dP:
  - Heat exchangers are wider than base cases
  - Large tubing size (6.4 cm) used throughout
  - Best applicable materials selected to minimize wall thicknesses



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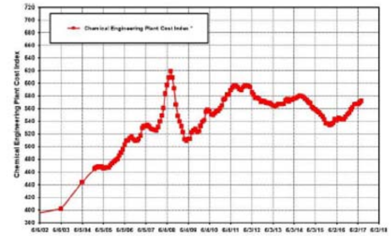
Design and Cost Estimate Basis



- Plant Sites
  - Generic plant site in Montana for Base and Test Cases 1, 2, 5, and 6 and in Midwest U.S. for Base and Test Cases 3 and 4
  - All sites are assumed to be clear and level with indoor construction
- Design Coals
  - PRB sub-bituminous coal for Base and Test Cases 1, 2, 5, and 6
  - Illinois #6 bituminous coal for Base and Test Cases 3 and 4
- Capital Cost Estimating Basis
  - AACE Class 5 study (-20 to -50% on low side; +30 to +100% on high side); AACE Guidelines were used for project and process contingencies
  - Estimates are expressed in June 2017 dollars; Chemical Engineering Plant Cost Index (CEPCI) was used to escalate base case costs
  - All-in union construction labor rates are \$81.28/hr for Midwest and \$61.45/hr for Montana

Relative cost difference between each base/test case is important

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O&M Cost and Cost of Electricity

- Total maintenance was based on a percentage of plant account cost

Account Description	% Maintenance	Account No.
Solid Handling and Storage	2.5%	1, 2, 10
Feedwater and Miscellaneous BOP Systems	2.0%	3
Boiler and Flue Gas Cleanup	2.5%	4, 5
CO_2 Condensing and Compression	1.5%	5A, 5B
Heat Recovery Steam Generator	2.0%	7
Power Cycle	2.0%	8 / 8B
Cooling Water	2.0%	9
BOP	1.5%	11, 12, 13, 14

  – A maintenance labor-to-materials ratio of 40:60 was assumed
- NETL QGESS Guidelines were used for:
  – Financial structure and economic assumptions
  – First-year power cost and LCOE
  – Cost of CO_2 avoided (includes \$10/tonne-CO_2 cost for CO_2 transportation & storage)
  – Cost of CO_2 captured (excludes cost for CO_2 transportation & storage)
  – Costs of CO_2 avoided/captured are relative to each reference case adjusted to 2017 dollars

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Costing Approach

Base Cases

- Costs determined by using identified base case costs as a starting point. Costs were adjusted by:
  - All Base Cases: Conversion to 2017$ using the CEPCI
  - Base Case 2: Steam conditions moved from 649° to 730°C

Test Cases

- Fired heater costs estimated based on designs by B&W and GE
- Air heater / recycle heater costs provided by Howden
- sCO_2 power cycle costs estimated based on cycle configurations by Echogen; sCO_2 power turbine costs provided by Doosan and Siemens
- Remaining costs were estimated using the appropriate QGESS scaling factors applied to the selected base cases

Emphasis on cost accuracy for fired heaters, sCO_2 turbines, and recuperators

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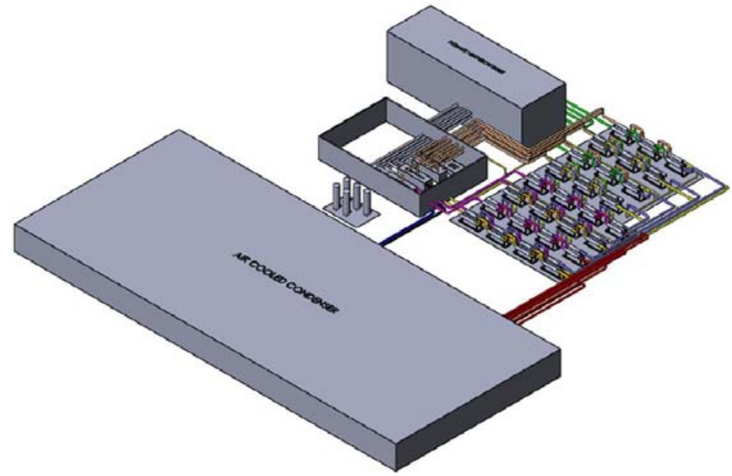
sCO_2 Power Cycle Costs



- Cost estimates for sCO_2 power cycle test cases
  - Power cycle instrumentation and control and electrical equipment and installation were scaled from the base cases
- When able, cost estimates were solicited from equipment suppliers
  - Recuperators (Vacuum Process Engineering [VPE]), power turbines (Doosan and Siemens), and ACC
- Installation costs estimates were provided by Louis Perry Group and used as the basis for piping, foundation, building, and installation
- When supplier cost estimates were not available, estimates were derived from Echogen's cost database and scaling laws from available quotes

Key components used vendor information and/or quotes

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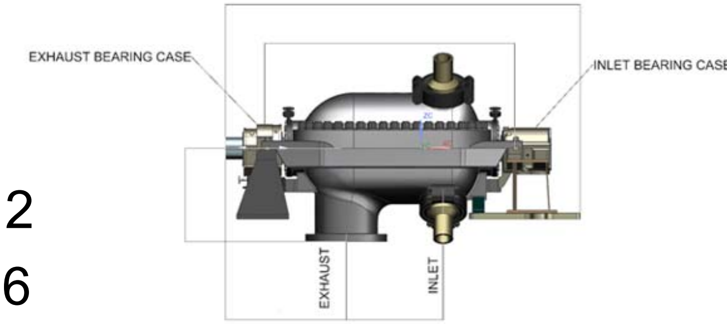
sCO_2 Power Turbine Costs



- Doosan provided cost estimates for Test Cases 1 and 2
- Siemens provided cost estimate for Test Cases 5 and 6
- "Bottoms-up" approach based on bill of materials for all major components. An allowance for secondary components (nuts, bolts, seals, retainers, etc.) was also included.
- Budgetary quotes were received for major components from established suppliers. When budgetary quotes were unavailable, costs for similar components (production or development) in other products were used.
- Engineering judgment was applied when pricing information from supplier or for similar components was not available
- For high-temperature cases, assumed price for nickel was used ($35/lb)

Full design was done for Test Cases 1 and 6 and Test Cases 2 and 5 were scaled

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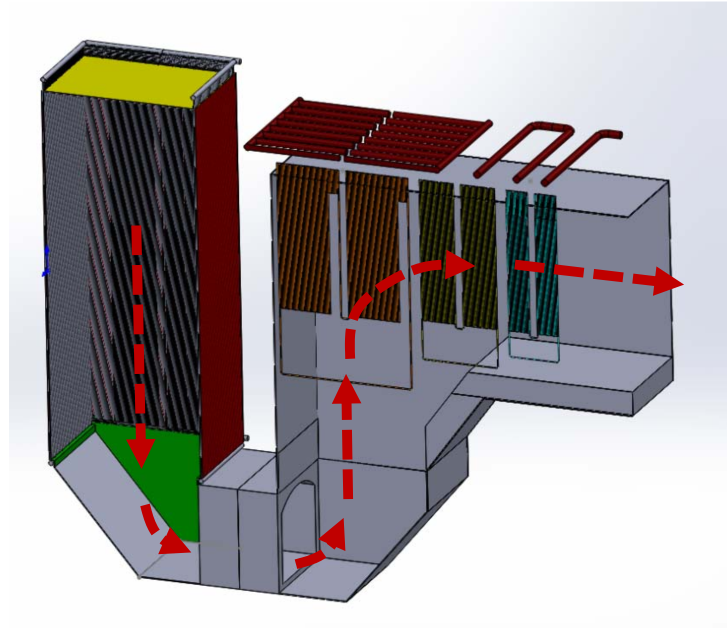
Fired Heater Cases 1, 2, 5, and 6 Costs



- B&W's inverted heater configuration
- Lower dP, higher efficiency driven designs, no reheat
- Base Cases 1 and 2: Greenfield site
- Base Case 5: Addition to an existing plant and used existing infrastructure, buildings, and facilities
- Test Cases 1 and 2: Modeled after 550-MW Oxy-PC NETL Base Case Boiler Systems
- Test Cases 5 and 6: Similar pressures and temperatures as 90-MW air-PC plant
- Costs were estimated using a combination of vendor quotes and in-house data. Equipment included fans, valves, flues / ducts, foundations, etc.
- Erection cost estimates provided by Babcock & Wilcox Construction Company

Detailed, bottoms-up approach was used

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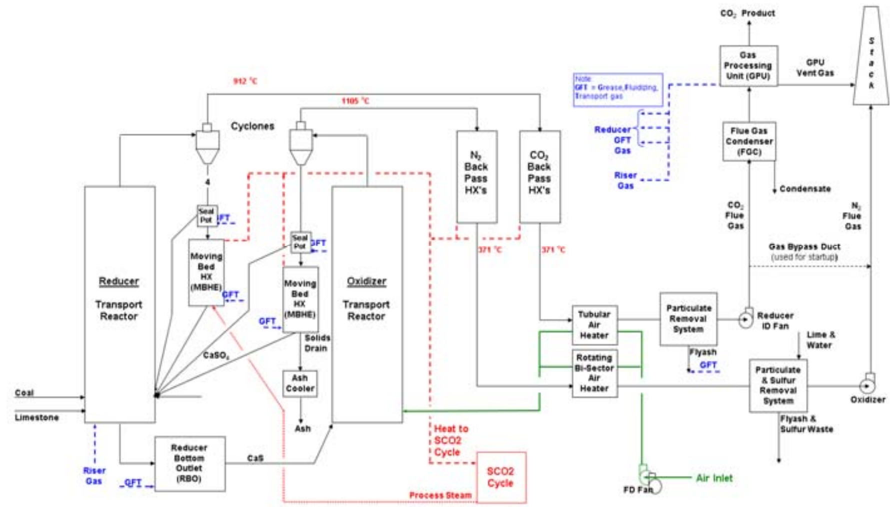
Fired Heater Cases 3 and 4 Costs



- GE's CLC fired heater cost estimate included:
  - Fuel and sorbent prep/feed (oxidizer side)
  - CO_2 purification (reducer side)
- Basis for LCL-C™ base case costs
  - Base Case 3 updated from Case 1 and Base Case 4 updated from Case 3 in DOE LCL-C™ Report (June 2013), respectively
  - Steam conditions changed, parts and heat and mass balance revised, all costs updated
- Development of LCL-C™ process island costs
  - Most equipment costs developed from internal or external quotes in DOE 2013 study
- Basis for erection costs
  - Based on actual recorded erection hours for a 280-MW fluidized-bed boiler
  - Erection hours adjusted for each case

Full update on base case costs and detailed test case cost analysis

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Summary Results

Case	Type	Net Power, MW	Turbine Inlet, °C / °C / MPa	Base	Test	Base	Test	Base	Test
				Net Efficiency, % (HHV)		Capital Costs, $M		LCOE, $/MWh	
1	Oxy-PC	550	593 / 593 / 24.1	31.0	33.0	$1894	$1955	150.5	150.7
2	Oxy-PC	550	730 / 760 / 27.6	34.3	38.0	$2038	$2122	156.3	157.3
3	CLC	550	593 / 593 / 24.1	35.8	38.5	$1357	$1410	142.9	142.5
4	CLC	550	730 / 760 / 27.6	40.4	43.0	$1535	$1510	145.0	138.7
5	Air-PC	90	593 / 24.1	33.0	36.0	$259	$357	126.0	160.5
6	Air-PC	90	730 / 27.6	---	41.0	---	$419	---	181.2

- Given the accuracy of the Class 5 estimate, this analysis shows that the capital costs are about the same
- Test Case 5 is not an apples-to-apples comparison to Base Case 5 as the turbine conditions were not matched. However, the high LCOE is unattractive.
- CLC beats PC by about 5% in LCOE. Reason enough to continue CLC?

No significant cost savings found in this analysis with its design and assumptions

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Capital Cost Details ($M)

Acct	Desc	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6
		Base	Test	Base	Test	Base	Test	Base	Test	Base	Test	Test
1	Coal Hdg	$53.6	$51.8	$50.5	$47.4	$58.1	$55.4	$54.0	$52.1	$18.9	$16.4	$15.1
2	Coal Prep	$18.6	$18.0	$17.5	$16.4	$22.2	$21.1	$21.0	$20.2	$9.2	$7.9	$7.3
3	FW & BOP	$93.7	$6.2	$84.6	$6.0	$106.9	$6.6	$91.8	$6.5	$13.9	$1.5	$1.4
4	Boiler	$914.4	$897.6	$1,082.8	$1,070.8	$350.4	$371.8	$464.6	$544.8	$68.6	$163.0	$211.9
5	FG Clean	$156.5	$145.9	$147.4	$133.2	$159.8	$152.0	$143.0	$123.7	$26.4	$23.1	$21.4
5B	CCS	$120.3	$116.4	$113.5	$106.4	$119.4	$113.8	$110.2	$106.4	$0.0	$0.0	$0.0
6	CTs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
7	HRSG, Duct	$100.4	$96.9	$85.6	$82.1	$47.2	$45.7	$45.0	$44.1	$10.3	$9.4	$9.0
8, 8B	STs sCO_2 Turb	$165.1	$381.8	$198.0	$416.1	$176.1	$428.8	$301.0	$402.9	$48.7	$67.4	$83.3
9	CW	$42.6	$0.0	$35.3	$0.0	$59.0	$0.0	$51.8	$0.0	$0.6	$0.0	$0.0
10	Ash	$20.7	$20.1	$19.7	$18.6	$37.8	$36.2	$35.8	$33.7	$4.8	$4.3	$4.0
11	Access	$91.7	$91.7	$88.0	$85.4	$97.7	$99.5	$94.0	$95.8	$18.6	$19.1	$18.1
12	I&C	$29.4	$29.4	$29.0	$28.8	$30.3	$30.5	$29.8	$30.0	$8.8	$8.9	$8.7
13	Improve	$17.6	$18.1	$17.6	$18.3	$18.5	$18.7	$18.9	$19.0	$8.4	$8.9	$9.2
14	Bldg	$69.4	$80.9	$69.0	$92.9	$73.2	$30.3	$74.1	$30.6	$22.0	$27.4	$29.2
Total	---	$1894.2	$1954.8	$2038.4	$2122.3	$1356.6	$1410.6	$1535.0	$1509.7	$259.2	$357.3	$418.7
% Dif	---		3.2%		4.1%		3.9%		-1.6%		37.9%	61.6%

- Boiler / fired heater (Account 4) and power cycle (Account 8 / 8B) costs dominate
- Other accounts only differ by minor amounts due to efficiency differences

Areas to attack to reduce costs remain the fired heater and power cycle

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Boiler and Power Island Capital Costs

Boiler / Fired Heater Costs, $M	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Base Case	$532.5	$723.8	$375.9	$468.9	$75.9	---
Test Case	$576.6	$794.8	$395.4	$476.7	$180.5	$231.7

Power Cycle Costs, $M	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Base Case	$300.0	$320.2	$341.0	$428.3	$69.9	---
Test Case	$381.8	$416.1	$428.8	$402.9	$67.4	$83.3

- Test Cases 1, 2, 3, and 4 fired-heater costs are not much more than base case boilers. Test Case 5 is at higher temperatures.
- sCO_2 power islands are more expensive than originally thought; turbines and recuperators are the principal costs

Trading off efficiency to reduce capital costs may be required

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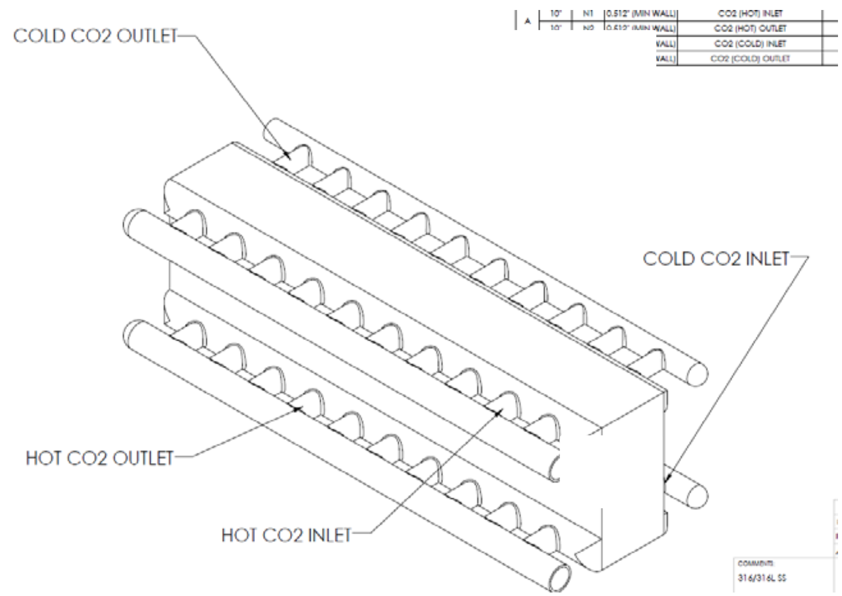
Recuperators

Case	Duty, MW	UA, kW/K	Sections Required	Cost ($M)	% of Cycle
1 – LTR	913	260,886	38	135.3	54%
1 – HTR	1,201	60,468	12	41.8	
2 – LTR	756	130,846	20	66.6	34.8%
2 – HTR	1,237	66,948	14	57.8	
3 – LTR	841	309,339	42	158.0	53.3%
3 – HTR	1,373	69,370	10	37.2	
4 – LTR	872	162,102	22	72.4	34%
4 – HTR	1,194	68,801	12	44.4	
5 – LTR	143	40.176	5	17.5	42.9%
5 – HTR	250	10,969	2	7.4	
6 – LTR	120	28,345	4	13.1	32.7%
6 – HTR	250	12,522	3	10.3	



- All recuperators quoted by VPE – printed circuit heat exchanger type
- Design was aggressive in terms of pressure drop and overall UA to maximize efficiency
- VPE indicated there are two areas that can be investigated for cost reduction:
  - Increase allowable hot-side sCO_2 pressure drop above the 1 bar limit
  - Reduce the target recuperator effectiveness to 96%

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O&M Cost Details

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6
$1000/yr	Base	Test	Base	Test	Base	Test	Base	Test	Base	Test	Test
Operating Jobs per Shift	14	14	14	14	14	14	14	14	6	6	6
Fixed O&M Costs											
Administrative & Support Labor	6199	6301	6570	6715	5010	5157	5334	5216	1408	1644	1789
Operating Labor	7972	7972	7972	7972	8609	8609	8609	8609	3416	3416	3416
Maintenance Labor	16,824	17,233	18,309	18,887	11,431	12,018	12,725	12,256	2214	3159	3738
Property Taxes and Insurance	37,884	39,097	40,768	42,446	27,132	28,308	29,936	28,571	5183	7147	8374
Total Fixed O&M	68,879	70,602	73,618	76,020	52,183	54,092	56,604	54,653	12,221	15,366	17,318
Variable O&M Costs											
Maintenance Material	25,237	25,849	27,463	28,331	17,147	18,027	19,088	18,384	3321	4739	5608
Consumables											
Bottom Ash Disposal	583	549	531	479	5798	5388	5172	5315	104	82	72
Chemicals	3729	1958	3280	1704	23,863	22,296	21,077	21,380	2172	1779	1564
Fly Ash Disposal	3478	3271	3160	2850	1449	1347	1293	1327	611	486	427
Water	3683	368	3124	312	3358	3120	3217	3217	651	586	514
Other Consumables	0	0	0	0	107	100	94	95	0	0	0
Total Variable O&M	36,709	31,995	37,557	33,676	51,722	50,279	49,941	49,717	6858	7671	8185

Variable O&M lower due to efficiency; Fixed O&M higher due to capital costs

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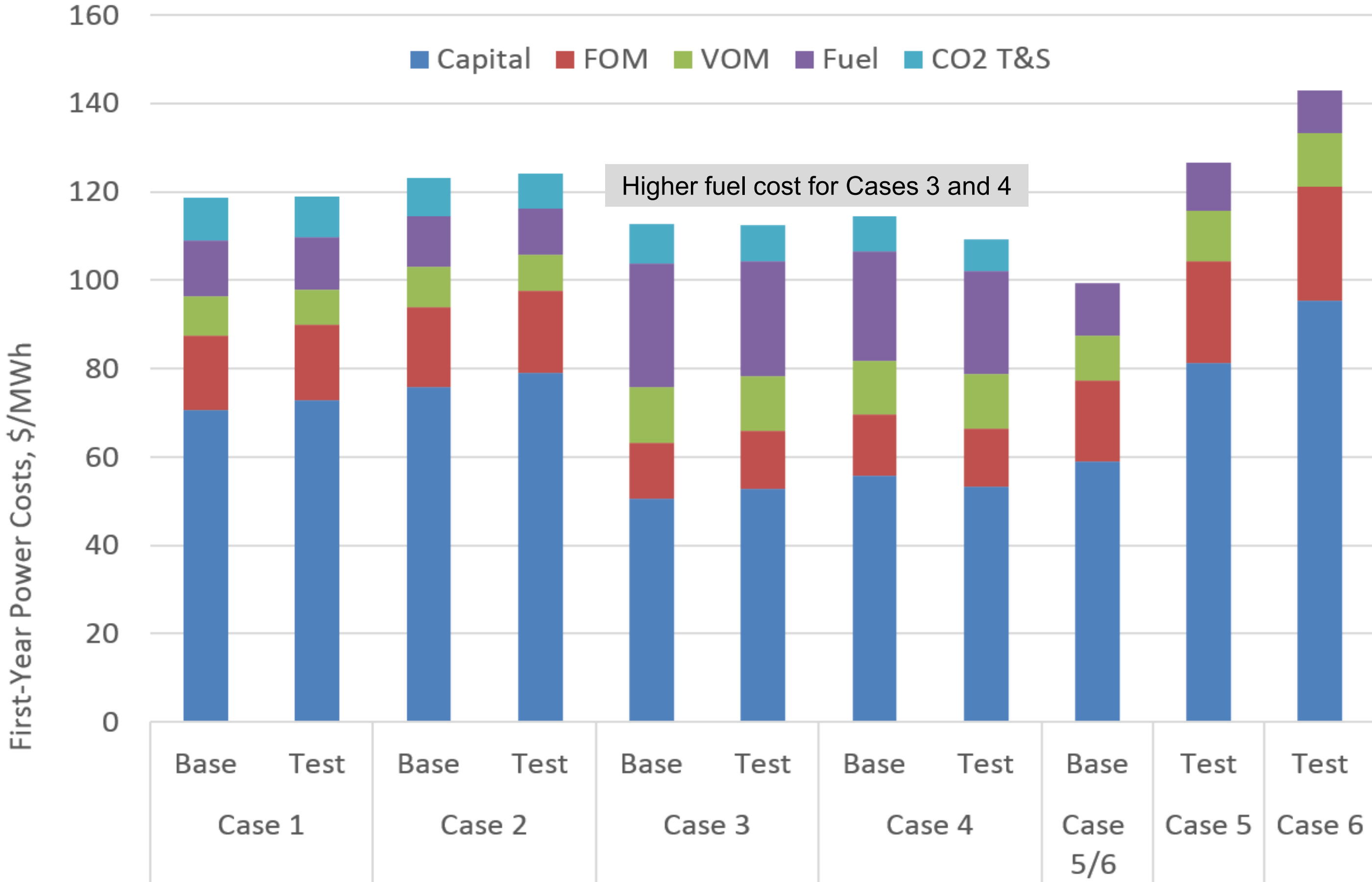
LCOE Chart



Capital cost increases counteract efficiency drop gains

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Conclusions

- sCO_2 power cycles in this analysis did not show a cost advantage
- Things to consider to potentially improve economics:
  - Different sCO_2 power cycles, e.g., partial cooling, where CO_2 flow rates are less, and/or reheat cycles that have higher efficiency
  - Different heat exchanger types, e.g., micro-tube
  - Sacrifice efficiency to reduce capital costs (e.g., reduce effectiveness on recuperators)
  - Improve cost fidelity, especially for higher-temperature sCO_2 power turbines
  - Focus on locations with high fuel costs and/or low labor rates where efficiency has more impact on LCOE
  - Water cooling vs. air cooling

sCO_2 power cycles have efficiency advantages, but work needs to be done on costs

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