Center for Applied Energy Research

Cost Analysis of the UKy-CAER Transformative CO_2 Capture System

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Outline

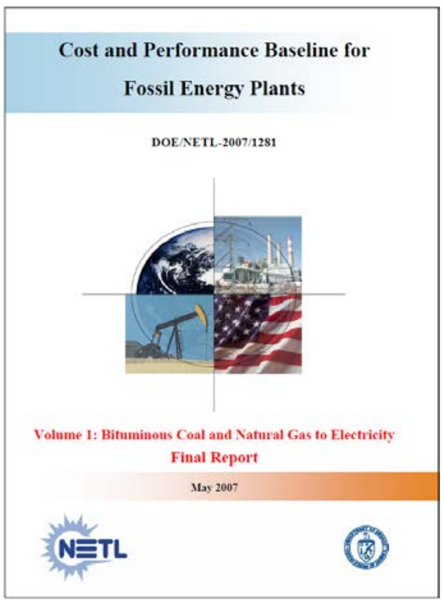
- Reference Cases (RCs)
- UKy-CAER CCS Technology
- UKy-CAER TEAs and Cost Estimations
- Uky-CAER CCS Cost Estimation Compared to RC B12B

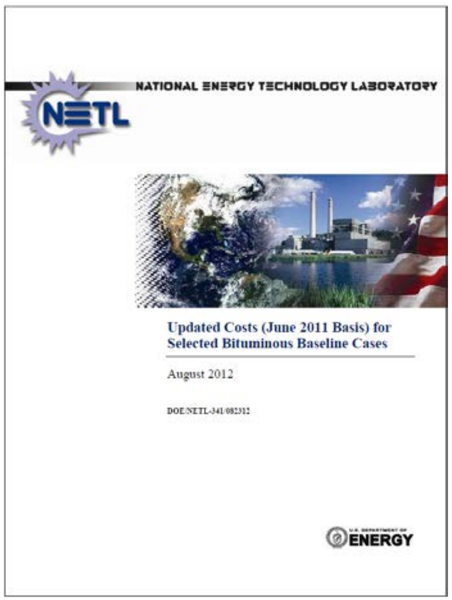
Take Away Points

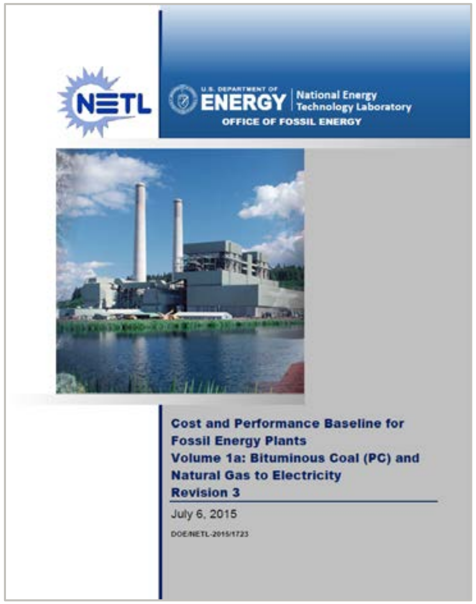
1. The UKy-CAER CCS has advantages, regardless of the Reference Case used for comparison.
2. Enhanced absorber mass transfer, high absorber inlet CO_2 concentration, leaner solution feed to the absorber, split rich stripper feed and smaller columns all contribute to lower capital costs.
3. The estimated cost of CO_2 capture with the UKy-CAER CCS is $41.40/tonne CO_2 captured (excluding T&S), compared to the RC B12B cost of $58/tonne of CO_2.

Reference Cases

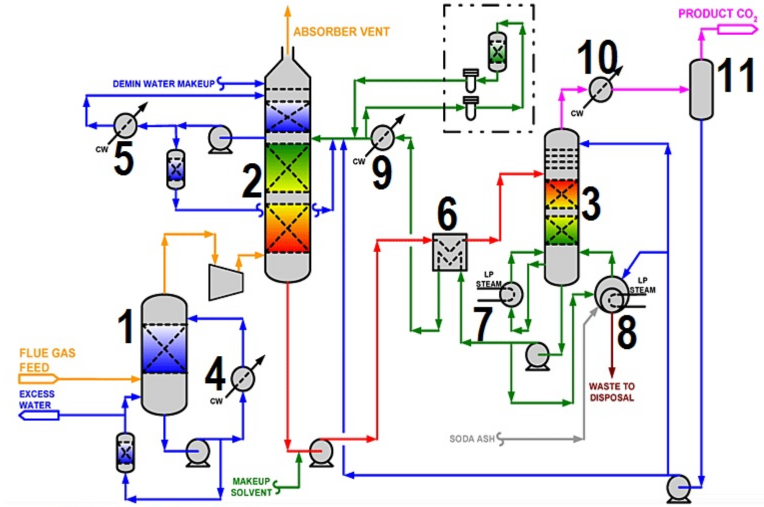
Set	Reference Case	Year Published	Steam Cycle	CCS Solvent	Used for Comparison by UKy-CAER
1	RC 9	2007	Subcritical	-	2012 TEA (Small Pilot CCS Project)
	RC 10	2007	Subcritical	MEA	
2	RC 11	2007	Supercritical	-	2016 TEA and 2017 Update (Large Pilot CCS Projects)
	RC 12	2007	Supercritical	MEA	
3	RC B12A	2015	Supercritical	-	Today
	RC B12B	2015	Supercritical	Second Generation	







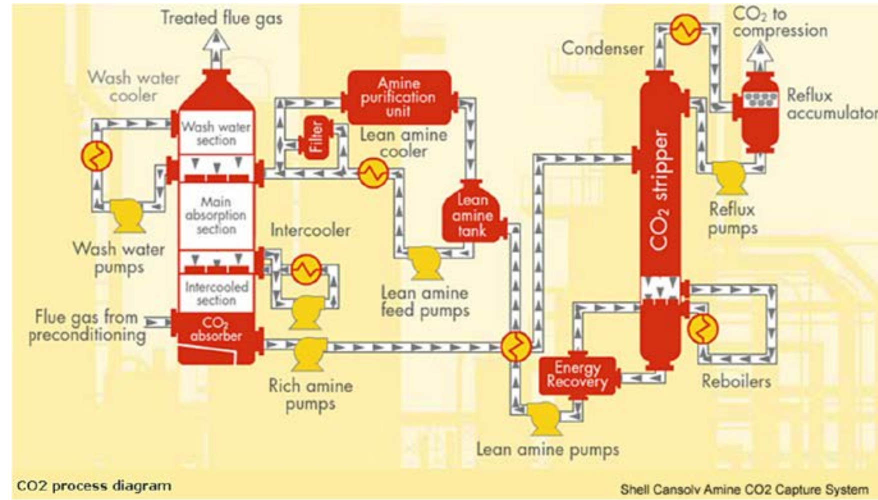
RC Comparison - CCS



RC 12 is a 1st Generation Technology using MEA.

Includes:

- Flue Gas Pretreatment
- Solvent Recovery
- Amine Filtering
- Solvent Regeneration = 1530 BTU/lb CO_2 Captured (3.56 GJ/tonne)



RC B12B is an Advanced, 2nd Generation Technology.

Includes:

- Flue Gas Pretreatment
- Solvent Recovery
- Absorber Intercooler
- Amine Purification
- Pressurized Stripping
- Solvent Regeneration = 1064 BTU/lb CO_2 Captured (2.47 GJ/tonne)

RC Comparison - Configuration

Supercritical PC Plant Study Configuration Matrix				
	RC 11	RC12	RCB12A	RCB12B
Steam Cycle, MPa/°C/°C	24.1/593/593	24.1/593/593	24.1/593/593	24.1/593/593
Coal	Illinois No. 6	Illinois No. 6	Illinois No. 6	Illinois No. 6
Condenser Pressure (mm Hg)	50.8	50.8	50.8	50.8
Boiler Efficiency, HHV%	88 *	88	89 *	89
Cooling Water to Condenser, °C	16	16	16	16
Cooling Water from Condenser, °C	27	27	27	27
Stack Temperature, °C	57	32	56	42
SO_2 Control	Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation
FGD Efficiency, %	98	98	98	98
NOx Control	LNB with OFA and SCR *	LNB with OFA and SCR	LNB with OFA, SCR and Polishing Scrubber *	LNB with OFA, SCR and Polishing Scrubber
SCR Efficiency, %	86	86	83	85
Ammonia Slip (End of Catalyst Life), ppmv	2	2	2	2
Particulate Control	Fabric Filter	Fabric Filter	Fabric Filter	Fabric Filter
Fabric Filter Efficiency, %	99.8	99.8	99.9	99.9
Ash Distribution, Fly/Bottom	80%/20%	80%/20%	80%/20%	80%/20%
SO_3 Control	DSI	DSI	DSI	DSI
Mercury Control	Co-benefit Capture *	Co-benefit Capture	Co-benefit Capture and ACI *	Co-benefit Capture and ACI
CO_2 Control	NA	* Econamine	NA	* Cansolv
Overall CO_2 Capture	NA	90.2	NA	90%
CO_2 Sequestration	NA	Off-site Saline Formation	NA	Off-site Saline Formation

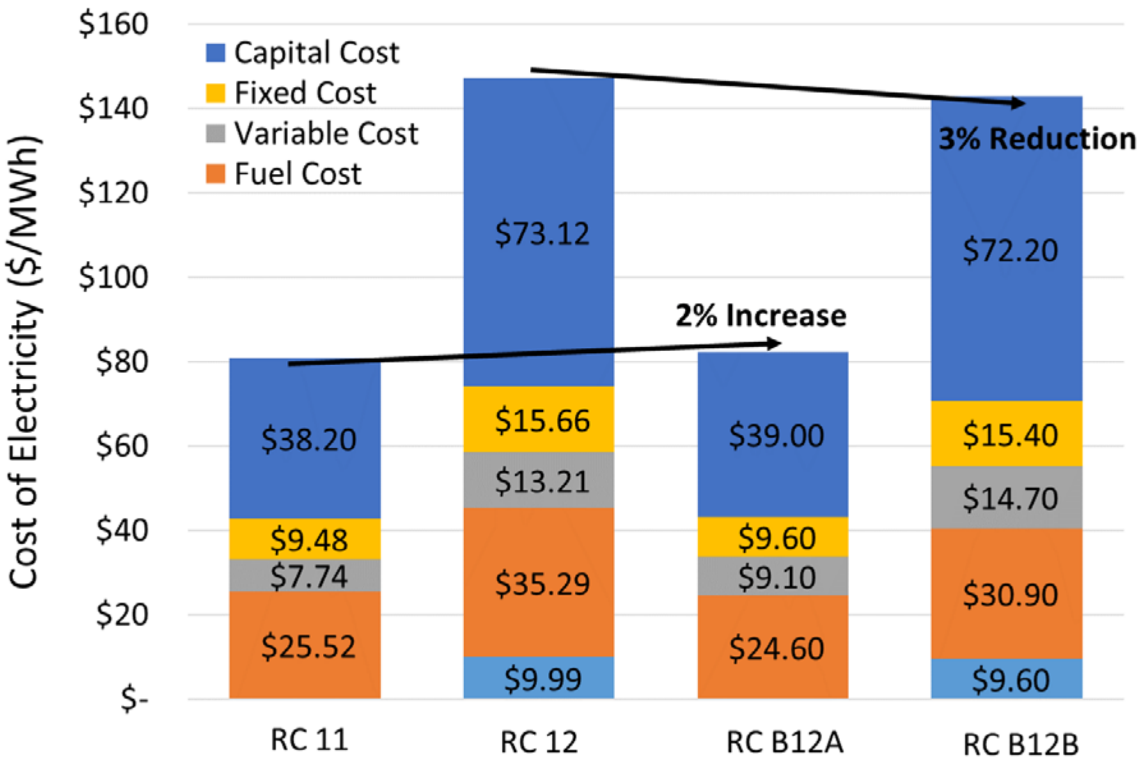
RC Comparison - Power

Plant Power Summary, kWe				
	RC 11	RC12	RCB12A	RCB12B
Coal Handling and Conveying	440	* 510	430	* 480
Pulverizer	2780	* 3850	2690	* 3370
Sorbent Handling & Reagent Preparation	890	* 1250	850	* 1070
Ash Handling	530	740	620	780
Primary Air Fans	1300	* 1800	1330	* 1670
Forced Draft Fans	1660	* 2300	1700	* 2130
Induced Draft Fans	7050	* 11120	6660	* 8350
SCR	50	70	40	60
Activated Carbon Injection	0	0	22	27
Dry Sorbent Injection	0	0	86	108
Baghouse	70	100	90	110
Wet FGD	2970	4110	2830	3550
CO_2 Capture/Removal Auxiliaries	0	* 20600	0	* 16000
CO_2 Compression	0	* 44890	0	* 35690
Miscellaneous BOP	2000	2000	2000	2000
Steam Turbine Auxiliaries	400	400	400	400
Condensate Pumps	800	* 560	800	* 640
Circulating Water Pumps	4730	* 10100	4520	* 7750
Ground Water Pumps	480	* 910	460	* 710
Cooling Tower Fans	2440	5230	2340	4010
Transformaer Losses	1820	2290	1820	2380
TOTAL	30410	* 112830	29688	* 91285

RC Comparison – Equipment Cost

Reference Case Comparison		RC 12	RC B12B	Percent Difference
Commercial Scale Plant Size (MW, net)		550	550	* 0%
Plant Efficiency, % (HHV basis)		28.4%	32.5%	* 14%
Net Plant Heat Rate, BTU/kWh HHV		12,002	10,508	-12%
Capital Costs (2011$/KW)		$ 3,563	$ 3,526	-1%
Equipment Costs ($x1000, 2011$)				
	Item/Description			
1	COAL & SORBENT HANDLING	$ 56,286	$ 52,286	* -7%
2	COAL & SORBENT PREP & FEED	$ 27,055	$ 24,983	* -8%
3	FEEDWATER & MISC. BOP SYSTEMS	$ 123,565	$ 112,150	* -9%
4	PC BOILER	$ 437,215	$ 400,793	* -8% ←
5	FLUE GAS CLEANUP	$ 196,119	$ 197,475	* 1%
5B	CO_2 REMOVAL & COMPRESSION	$ 593,497	$ 632,139	* 7%
5B.1	CO_2 Removal System	$ 505,963	$ 533,757	* 5%
5B.2	CO_2 Compression & Drying	$ 87,534	$ 98,381	* 12%
6	COMBUSTION TURBINE/ACCESSORIES	$ -	$ -	
7	HRSG, DUCTING & STACK	$ 45,092	$ 45,027	0%
8	STEAM TURBINE GENERATOR	$ 166,965	$ 178,176	* 7%
9	COOLING WATER SYSTEM	$ 73,311	$ 62,254	* -15%
10	ASH/SPENT SORBENT HANDLING SYSTEM	$ 18,252	$ 19,028	* 4%
11	ACCESSORY ELECTRIC PLANT	$ 100,255	$ 93,584	* -7%
12	INSTRUMENTATION & CONTROL	$ 31,053	$ 31,654	* 2%
13	IMPROVEMENTS TO SITE	$ 18,332	$ 18,063	* -1%
14	BUILDINGS & STRUCTURES	$ 72,402	$ 71,531	* -1%
TOTALS		$ 1,959,399	$ 1,939,143	* -1%

COE of RC B12B Compared to RC 12



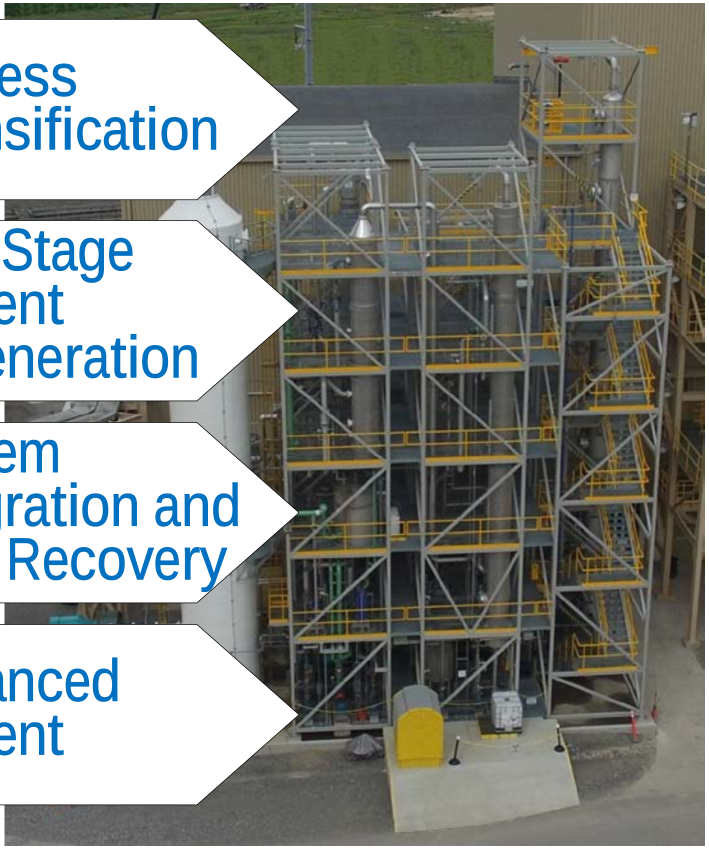
<u>RC B12B Advantages over RC 12:</u>

1) Second Generation Solvent
2) Pressurized Solvent Regeneration

UKy-CAER CCS Costs Reported

2012 TEA Performed by EPRI and WP	2016 TEA Performed by EPRI and WP	2017 Estimates Based on 2016 TEA	December 2018 Estimates Based on 2016 TEA	March 2019 Estimates Based on 2016 TEA By EPRI
Compared to RC 10	Compared to RC 12	Compared to RC 12	Compared to RC B12B	Compared to RC B12B
Constant Coal Feed Rate	Constant Coal Feed Rate	Constant Coal Feed Rate	Constant Coal Feed Rate	Constant Net Power Output
UKy-CAER CCS Included:	UKy-CAER CCS Included:	UKy-CAER CCS Included:	UKy-CAER CCS Included:	UKy-CAER CCS Included:
Advanced Solvent	Advanced Solvent	Advanced Solvent	Advanced Solvent	Advanced Solvent
Two Stage Stripping	Two Stage Stripping	Two Stage Stripping	Two Stage Stripping	Two Stage Stripping
Heat Integration	Heat Integration	Heat Integration	Heat Integration	Heat Integration
Tall Columns	Tall Columns	Reduced Column Sizes	Reduced Column Sizes	Reduced Column Sizes
		Split Rich Stripper Feed	Split Rich Stripper Feed	Split Rich Stripper Feed
		Exergy Loss Minimization	Exergy Loss Minimization	Exergy Loss Minimization

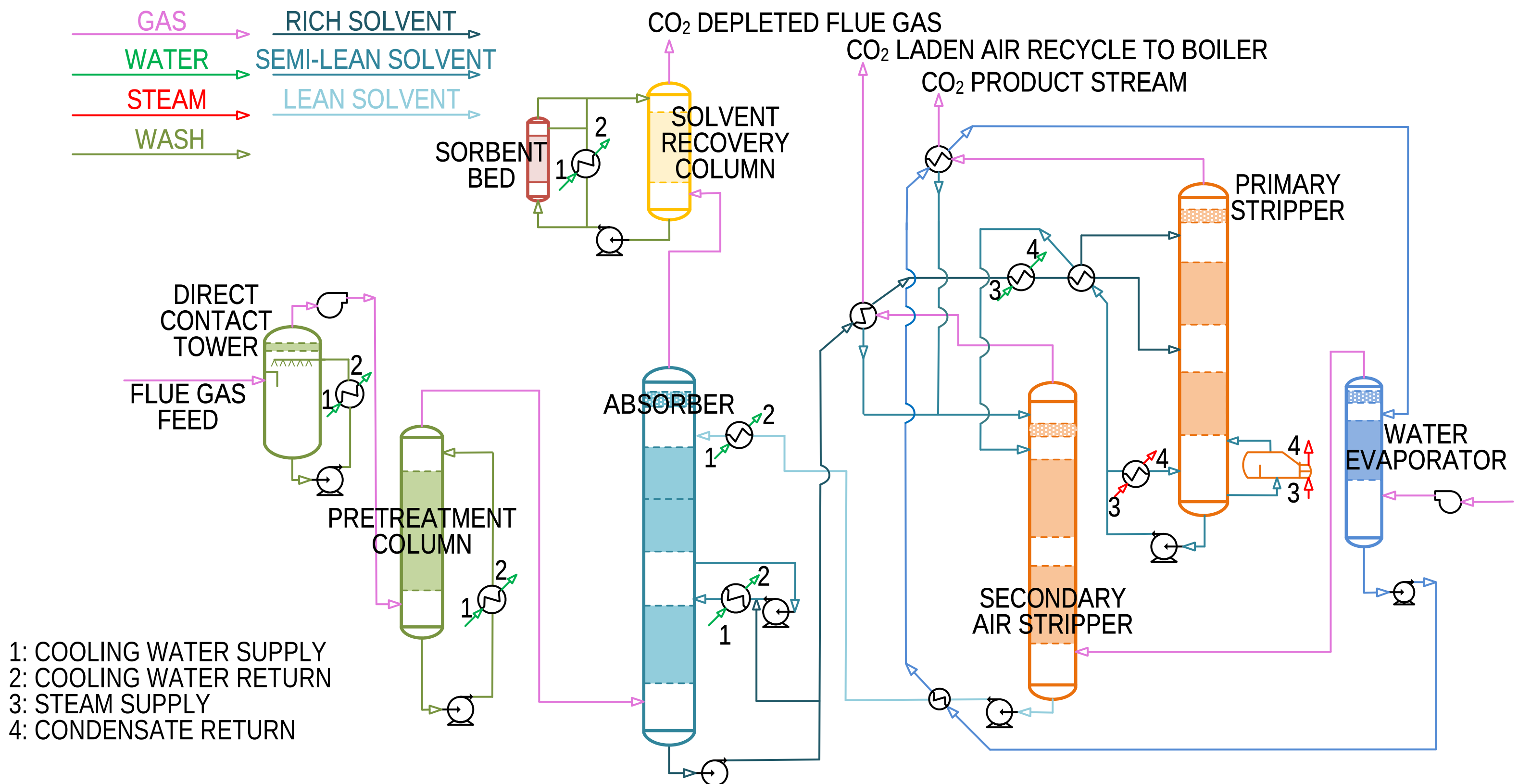
UKy-CAER Approach to CCS



- Process Intensification
- Two-Stage Solvent Regeneration
- System Integration and Heat Recovery
- Advanced Solvent

- Smaller column heights
- Discretized packing
- Absorber T profile and flooding control
- Absorber pump around
- Pressurized primary stripper
- Split rich primary stripper feed to reduce the H_2O/CO_2 ratio in the stripper outlet and supply secondary vapor source for CO_2 stripping
- Exergy loss minimization in steam extraction

UKy-CAER CCS



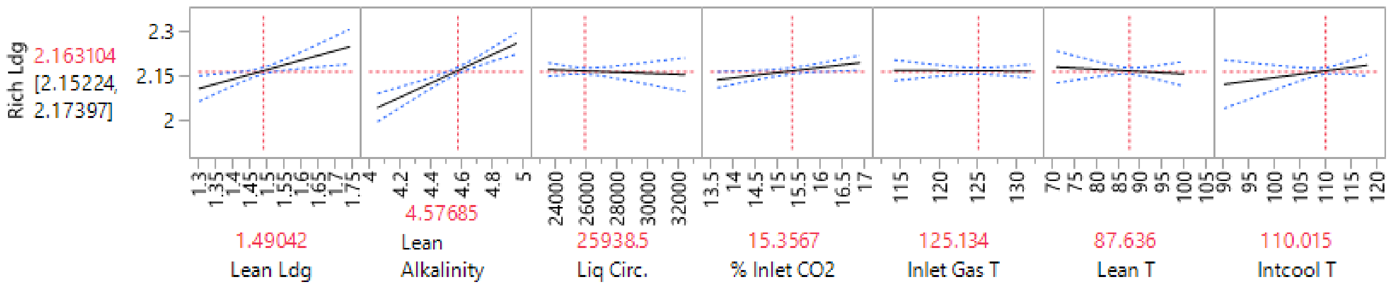
Includes:

- Flue Gas Pretreatment
- Solvent Recovery
- Absorber Intercooling
- Pressurized Primary Stripping
- Heat Recovery Loop, Piping and Pump
- Secondary Stripper, Overhead Condenser, Blower, Lean Amine Pump
- Secondary Stripper Gas Outlet Recycle Line Back to Boiler
- Solvent Regeneration = 900 BTU/lb CO_2 Captured (2.10 GJ/tonne)

0.7 MWe Small Pilot CCS Output: Solvent Regeneration Energy

Performance Compared to 30 wt% MEA	Advanced Solvent A	Advanced Solvent B	Advanced Solvent C
Energy Penalty	27% savings	~30% savings	20-25% savings
Solvent Circulation Rate	~35-45% reduction	~40% reduction	~30% reduction
Cyclic Capacity	~1.5X	~2X	~1.5X
Viscosity	2.5 – 3X	3 – 3.5X	~1.5X
Surface Tension	~0.6X	-1.1X	~1.0X
Degradation Products	Low	Low	Low
Solvent Regeneration Energy Measured at UKy-CAER CCS	1022 Btu/lb CO_2 on 0.7 MWe Small Pilot, 61% of MEA on 0.1 MWth Bench	1200-1400 BTU/lb CO_2 on 0.7 MMWe, 52% of MEA on 0.1 MWth Bench	1070-1600 BTU/lb CO_2 on 0.7 MMWe, 68% of MEA on 0.1 MWth Bench

0.7 MWe Small Pilot CCS Output: Column Height Reduction



	2016 TEA	Updated UKy-CAER Equipment Size		
Scale	Normalized 550 MWe	Normalized 550 MWe	~170 TPD	550 MWe
Absorber	41' dia., 138' T/T, 118' pkg ht, ΔP = 1.79 psi	41' dia., 80' T/T, 60' pkg ht, ΔP = 1.06 psi	23' dia., 110' T/T, 60' pkg ht	48' dia., 68' T/T, 40' pkg ht
Primary Stripper	19' dia., 110' T/T, 95' pkg ht, ΔP = 7 psi	19' dia., 60' T/T, 45' pkg ht, ΔP = 4.2 psi	14' dia., 56' T/T, 26' pkg ht	27' dia., 38' T/T, 33' pkg ht
Secondary Stripper	21' dia., 92' T/T, 72' pkg ht, ΔP = 12.6 psi	21' dia., 55' T/T, 35' pkg ht, ΔP = 7.5 psi		
Direct Contact Cooler	47' dia., 110' T/T, ΔP = 1.7 psi	47' dia., 65' T/T, ΔP = 1.0 psi	23' dia., 49' T/T, 16.5' pkg ht, ΔP = 1 psi	

Statistical analysis of small pilot CCS data show that the absorber is tall enough to approach equilibrium rich loading.

Updated Equip. Cost Estimates

	RC B12B	UKy-CAER CCS	Percent Difference
Commercial Scale Plant Size (MW, net)	550	550	0%
Plant Efficiency, % (HHV basis)	32.5%	34.0%	5%
Total Plant Costs (x 1000 2011$)			
Item/Description			
COAL & SORBENT HANDLING	$ * 52,286	$ * 50,810	-3%
COAL & SORBENT PREP & FEED	$ * 24,983	$ * 24,242	-3%
FEEDWATER & MISC. BOP SYSTEMS	$ * 112,150	$ * 112,798	1%
PC BOILER	$ * 400,793	$ * 388,308	-3%
FLUE GAS CLEANUP	$ * 197,475	$ * 190,974	-3%
CO_2 REMOVAL & COMPRESSION	*$ * 632,139*	$ * 362,742	-43%
CO_2 Removal System	*$ * 533,757*	$ * 267,082	-50%
CO_2 Compression & Drying	*$ * 98,381*	$ * 95,659	-3%
DUCTING & STACK	$ * 45,027	$ * 44,664	-1%
STEAM TURBINE GENERATOR	$ * 178,176	$ * 173,158	-3%
COOLING WATER SYSTEM	$ * 62,254	$ * 61,210	-2%
ASH/SPENT SORBENT HANDLING SYSTEM	$ * 19,028	$ * 18,546	-3%
ACCESSORY ELECTRIC PLANT	$ * 93,584	$ * 90,164	-4%
INSTRUMENTATION & CONTROL	$ * 31,654	$ * 31,244	-1%
IMPROVEMENTS TO SITE	$ * 18,063	$ * 17,693	-2%
BUILDINGS & STRUCTURES	$ * 71,531	$ * 70,751	-1%
TOTAL	$ 1,939,143	$ 1,637,302	-16%

Constant Net Power Output, Higher Thermal Efficiency

Lower: Smaller power plant size

Higher: Equipment related to exergy loss minimization strategy

Lower: higher inlet CO_2 concentration, enhanced absorber mass transfer, split rich stripper feed, discretized packing, smaller columns

Lower: Takes into account the additional duct from secondary stripper back to boiler

Lower: heat integration and small cooling tower and fan

Lower: Takes into account additional CCS equipment and bigger footprint

CO_2 Removal System Equipment Cost

From TEA Performed under DE-FE0026497 Equipment List with Columns Oversized				
Description	Quantity	Equipment and Materials Cost ($)	Labor Cost ($)	Bare Erect Cost ($)
Pre-treatment Tower	2 op	$ 6,073,043.85	$ 4,858,435.08	$ 10,931,478.93
CO_2 Absorber	2 op	$ 48,583,511.59	$ 32,389,007.72	$ 80,972,519.31
Primary Stripper	2 op	$ 17,343,192.33	$ 10,486,581.41	$ 27,829,773.74
Reclaimer	1 op	$ 1,648,333.33	$ 1,318,666.67	$ 2,967,000.00
Air Stripper	2 op	$ 16,549,871.33	$ 11,033,247.56	$ 27,583,118.89
Reboiler	2 op	$ 6,301,601.83	$ 4,201,067.89	$ 10,502,669.72
Lean/Rich Exchanger	2 op	$ 5,509,180.47	$ 3,505,842.11	$ 9,015,022.58
Recycle Air Cooler #1	2 op	$ 3,086,906.50	$ 2,057,937.66	$ 5,144,844.16
CO_2 Cond #3	2 op	$ 1,924,047.86	$ 1,282,698.57	$ 3,206,746.43
CO_2 Condenser #4	2 op	$ 202,942.55	$ 135,295.03	$ 338,237.58
Absorber Intercooler	2 op	$ 2,701,219.38	$ 1,800,812.92	$ 4,502,032.29
Lean Cooler	2 op	$ 1,992,470.30	$ 1,328,313.53	$ 3,320,783.83
Recycle Air Cooler #2	2 op	$ 536,045.67	$ 357,363.78	$ 893,409.45
DCC Cooler	1 op	$ 1,085,211.21	$ 723,474.14	$ 1,808,685.35
Lean Solution Pump	2 op & 2 spare	$ 13,693,978.90	$ 13,693,978.90	$ 27,387,957.81
Rich Solution Pump	2 op & 2 spare	$ 7,200,561.07	$ 7,200,561.07	$ 14,401,122.13
Primary Stripper Pump	2 op & 2 spare	$ 4,436,329.41	$ 4,436,329.41	$ 8,872,658.83
Intercooler Pump	2 op & 1 spare	$ 3,919,149.67	$ 3,919,149.67	$ 7,838,299.34
Solvent Make-up Pump	1 op & 1 spare	$ 173,600.00	$ 173,600.00	$ 347,200.00
DCC Pump	1 op & 1 spare	$ 3,292,828.47	$ 3,292,828.47	$ 6,585,656.95
ID Fan	2 op	$ 6,524,033.38	$ 3,262,016.69	$ 9,786,050.07
Air Stripper Blower	2 op	$ 1,069,765.75	$ 534,882.87	$ 1,604,648.62
Total		$ 153,847,824.84	$ 111,992,091.17	$ 265,839,916.01
Allowance for Interconnections		$ 13,122,379.48	$ 6,674,403.11	$ 19,796,782.59
Grand Total		$ 166,970,204.32	$ 118,666,494.27	$ 285,636,698.60

The air stripper, blower, condenser and pump are only 23% of the bare erect cost which is ~$40M.

Reduced Column Heights:
Direct Contact Cooler: 110 to 65 ft.
Absorber: 138 to 82 ft.
Primary Stripper: 95 to 56 ft.
Secondary Stripper: 92 to 55 ft.

5B. CO_2 Removal and Compression

Case 12

	Item/Description	Bare Erected Cost	Eng'g CM H.O. & Fee	Process Contingencies	Project Contingencies	Total Plant Cost ($/1000)
5B.1	CO_2 Removal System	$ 326,057	$ 30,367	$ 65,211	$ 84,327	$ 505,963
5B.2	CO_2 Compression & Drying	$ 66,717	$ 6,228	$ -	$ 14,589	$ 87,534
	SUBTOTAL	$ 392,774	$ 36,595	$ 65,211	$ 98,916	$ 593,497

UKy-CAER CCS Compared to RC 12, Constant Coal Feed Rate

	Item/Description	Bare Erected Cost ($)	Eng'g CM H.O. & Fee	Process Contingencies	Project Contingencies	Total Plant Cost ($/1000)
5B.1	CO_2 Removal System	$ 201,906	$ 17,364	$ 34,930	$ 45,227	$ 299,426
5B.2	CO_2 Compression & Drying	$ 56,586	$ 5,286	$ -	$ 12,374	$ 74,246
	SUBTOTAL	$ 258,492	$ 22,650	$ 34,930	$ 57,601	$ 373,672

Case B12B

	Item/Description	Bare Erected Cost	Eng'g CM H.O. & Fee	Process Contingencies	Project Contingencies	Total Plant Cost ($/1000)
5B.1	CO_2 Removal System	$ 359,822	$ 31,060	$ 62,120	$ 80,756	$ 533,757
5B.2	CO_2 Compression & Drying	$ 74,531	$ 7,453	$ -	$ 16,397	$ 98,381
	SUBTOTAL	$ 434,353	$ 38,513	$ 62,120	$ 97,152	$ 632,139

UKy-CAER CCS Compared to RC B12B, Constant Net Power Output

	Item/Description	Bare Erected Cost	Eng'g CM H.O. & Fee	Process Contingencies	Project Contingencies	Total Plant Cost ($/1000)
5B.1	CO2 Removal System	$ 180,048	$ 15,542	$ 31,084	$ 40,409	$ 267,082
5B.2	CO2 Compression and Drying	$ 72,469	$ 7,247	$ -	$ 15,943	$ 95,659
	SUBTOTAL	$ 252,517	$ 22,789	$ 31,084	$ 56,351	$ 362,742

10% Reduction Due to Smaller Amount of CO_2 Because of the to Lower Coal Feed Rate from RC 12 to B12B and from B12B to UKy-CAER CCS

50% Reduction in CO_2 Removal System Cost

Updated Power

POWER SUMMARY	Case B12B	UKy-CAER CCS	Percent Difference
NET POWER, kWe	550,000	550,000	0%
Net Plant Efficiency (HHV)	32.50%	33.97%	5%
As-Received Coal Feed (lb/hr)	495,578	473,362	-4%
Steam Turbine Power (Gross, kWe)	642,000	632,779	-1%
AUXILIARY LOAD SUMMARY, kWe			
Coal Handling & Conveying	480	458	-4%
Pulverizers	3,370	3,219	-4%
Sorbent Handling & Reagent Preparation	1,070	1,022	-4%
Ash Handling	780	745	-4%
Primary Air Fans	1,670	1,595	-4%
Forced Draft Fans	2,130	2,035	-4%
Induced Draft Fans	8,350	7,976	-4%
SCR	60	57	-4%
Activated Carbon Injection (kW)	27	26	-4%
Dry Sorbent Injection (kW)	108	103	-4%
Baghouse	110	105	-4%
Wet FGD	3,550	3,391	-4%
CO_2 Capture System Auxiliaries	16,000	10,867	-32%
CO_2 Compression	35,690	34,086	-4%
Miscellaneous Balance of Plant	2,000	1,910	-4%
Steam Turbine Auxiliaries	400	394	-1%
Condensate Pumps	640	611	-4%
Circulating Water Pump	7750	7,257	-6%
Ground Water Pumps	710	674	-5%
Cooling Tower Fans	4010	3,911	-2%
Transformer Losses	2380	2,153	-10%
TOTAL AUXILIARIES, kWe	91,000	82,595	-9%

Constant Net Power Output, Higher Thermal Efficiency

Lower: Smaller auxiliary load

Lower: Lower coal feed rate

Lower: Smaller blowers and pumps due to shorter columns

Lower: Lower Steam Turbine Power

Lower: Smaller HHV input due to higher thermal efficiency leads to lower water requirement and small cooling tower

Lower: Smaller gross power production

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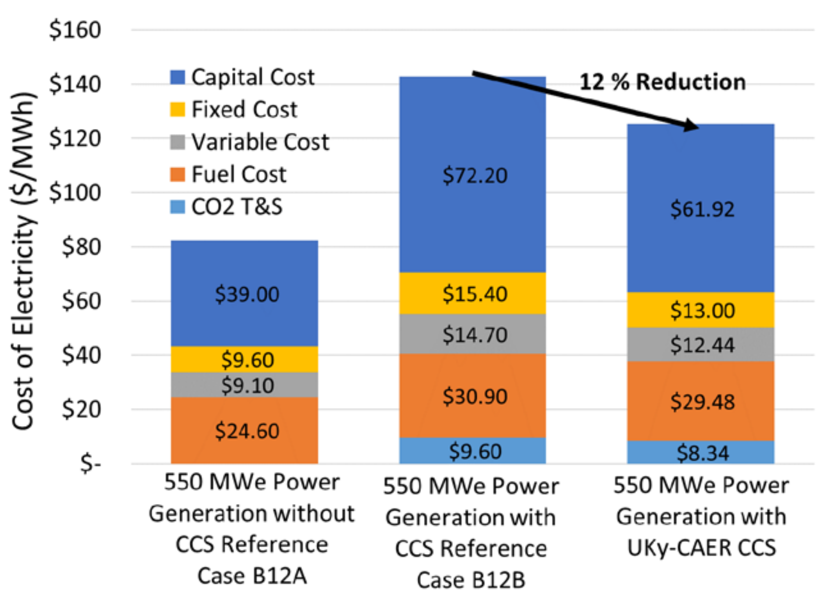
Updated COE and Cost of CO_2 Captured

	RC B12B	UKy-CAER CCS	Percent Difference
Net Power, Mwe	550	550	0%
Total Plant Cost (2011 $/kW)	3524	2977	-16%
Total Overnight Cost (2011$/kW)	4333	3660	-16%
Total As-Spent Cost (2011$/kW)	4940	4173	-16%
Cost of Electricity ($/MWh, 2011$)	133.2	116.9	-12%
CO_2 T&S Costs	9.6	8.3	-13%
Fuel Costs	30.9	29.5	-5%
Variable Costs	12.3	12.4	1%
Fixed Costs	15.4	13.0	-16%
Capital Costs	72.2	61.9	-14%
Cost of CO_2 Captured ($/tonne CO_2)	58.2	41.4	-29%



<u>UKy-CAER Advantages:</u>

1) Two Stage Solvent Regeneration
2) Pressurized Stripping
3) Split Rich Primary Stripper Feed
4) Advanced Solvent
5) CO_2 Recycle
6) High Solvent Cyclic Capacity, High Rich Loading and Low Lean Loading
7) Heat Integration
8) Exergy Loss Minimization

Next Steps

- CO_2 Preconcentrating Membrane
- Absorber Temperature Profile Control

Acknowledgements

Some results presented were collected under awards:

Application of a Heat Integrated Post-combustion CO_2 Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant, DE-FE0007395

Large Pilot CAER Heat Integrated Post-combustion CO_2 Capture Technology for Reducing the Cost of Electricity, DE-FE0026497

UKy-CAER Heat-integrated Transformative CO_2 Capture Process in Pulverized Coal Power Plants, DE-FE0031583

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