Techno-Economic Analysis of 550 MWe subcritical PC power plant with CO_2 capture

DE-FE0007453

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LeadIng.

THE LINDE GROUP

DOE-NETL, Pittsburgh, PA
May 4, 2012

Presentation outline

- Basis for techno-economic assessment
- PCC plant design and process integration options
- Detailed results of techno-economic analysis
- Conclusions
- Response to DOE-NETL review questions

Basis for techno-economic assessment for 550 MW_e power plant with 90% CO_2 capture

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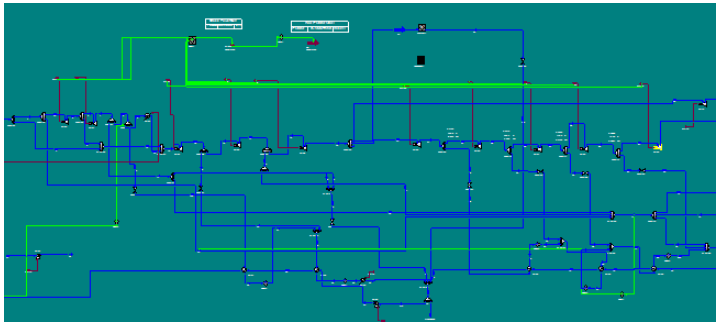
Specifications and Design Basis

identical to DOE/NETL Report 2007/1281

as per DE-FOA-0000403 requirements

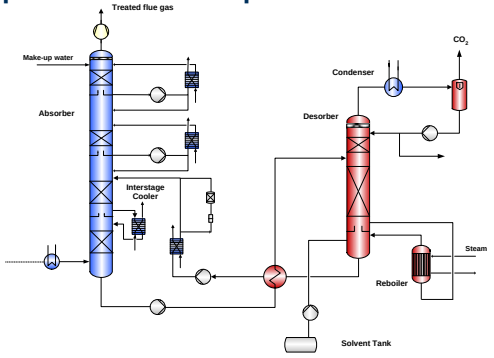
- Bituminous Illinois #6 Coal Characteristics
- Site Characteristics and Ambient Conditions
- Pulverized Coal Boiler Design
- Subcritical Steam Turbine Design
- Steam Cycle Conditions
- Environmental Controls and Performance
- Balance of Plant
- Economic Assumptions and Methodology

Computational Platform

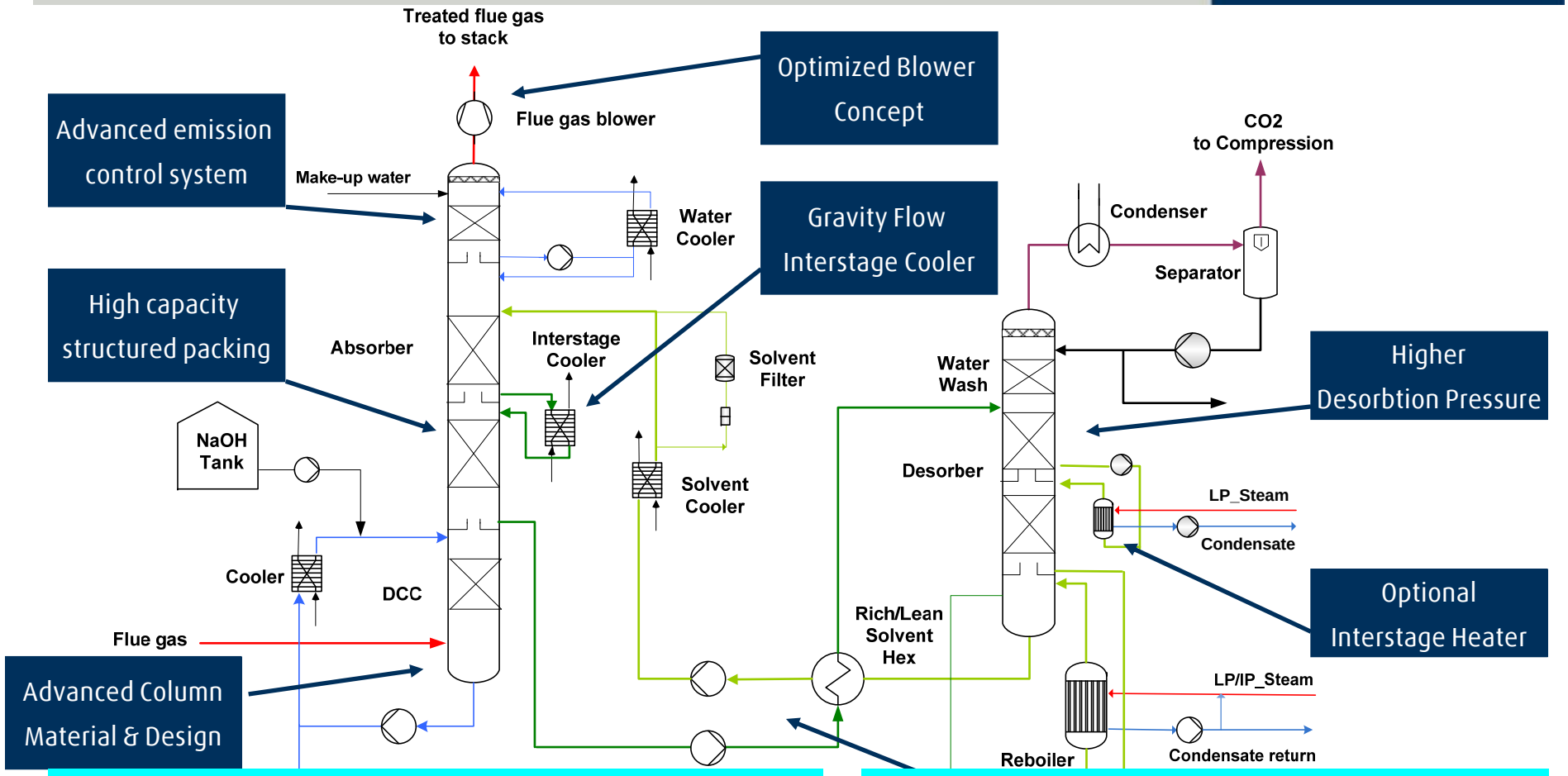


UniSim Design Suite R390, integrated with

- Brian Research & Engineering ProMax® software for PCC parametric optimization
- BASF's proprietary package for rigorous solvent performance predictions



Linde-BASF advanced PCC plant design*



~ 20% reduced cooling duty requirements

~ 22% reduced make-up water requirements

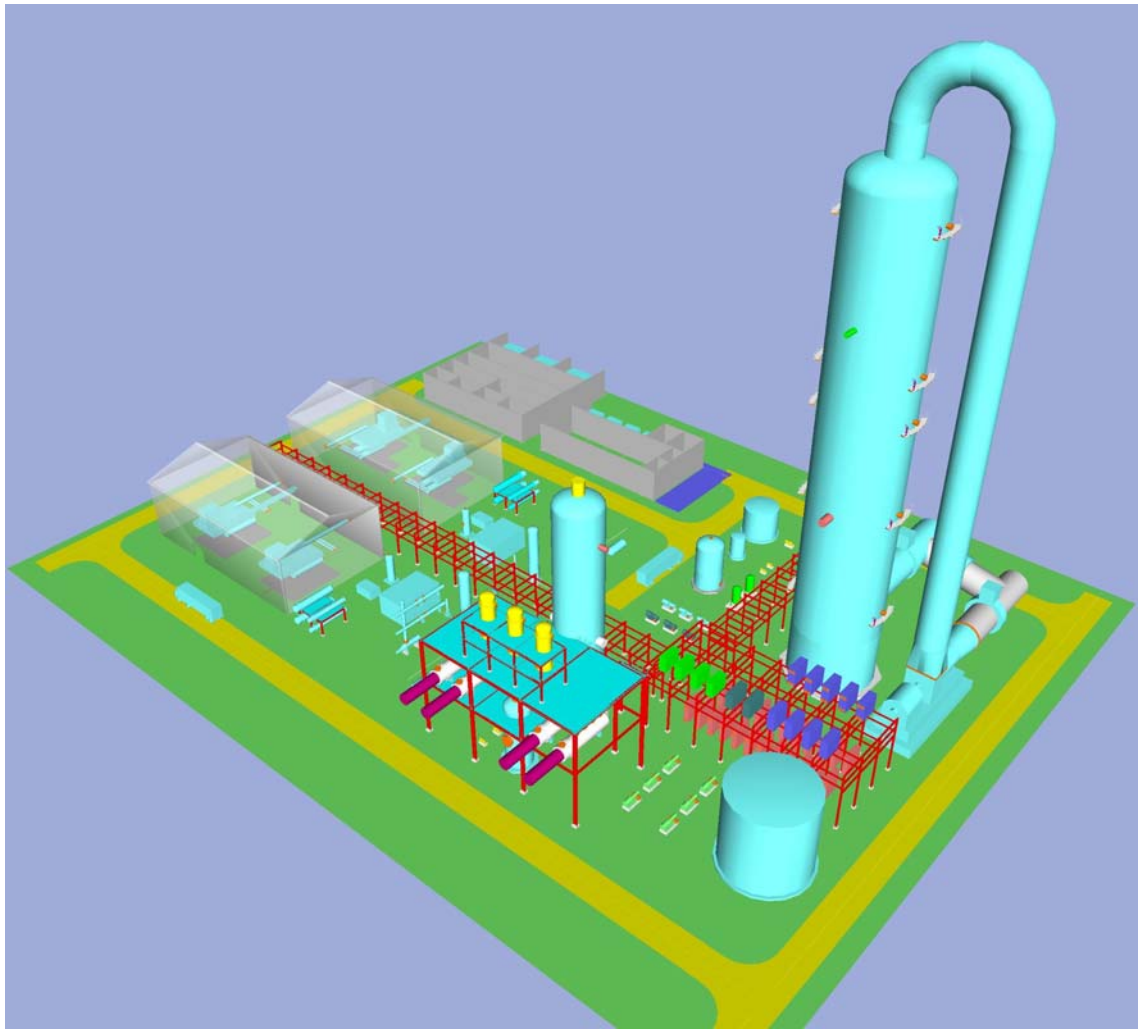
~ 13% reduced flue gas blower duty requirement

~ 23% reduced duty for CO_2 compression

21-32% reduced reboiler duty

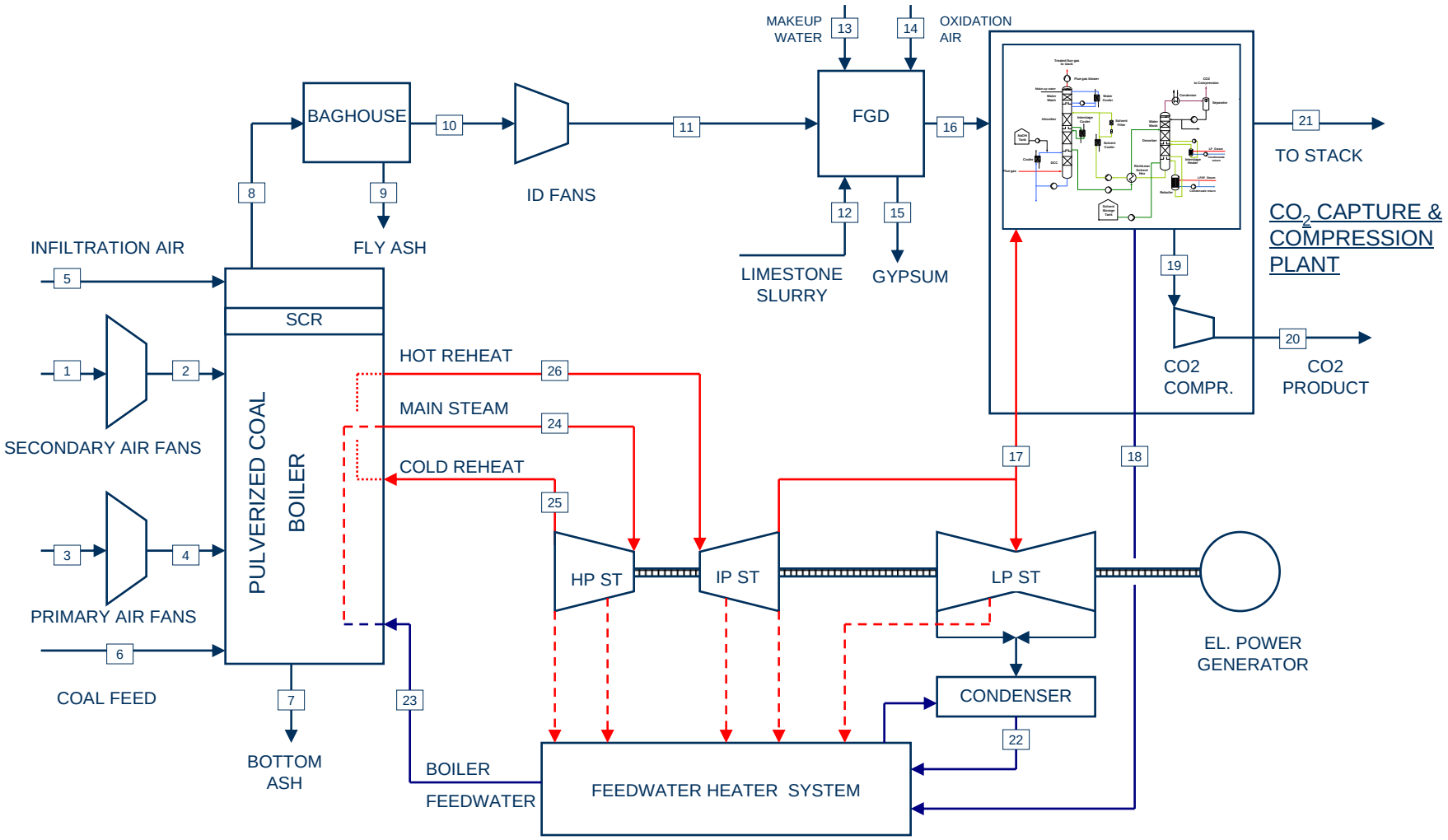
* Patent Applications 2010-2012

Linde-BASF PCC plant design for 550 MWe PC power plant



- Single train PCC design for up to 13,500 TPD CO_2 capture
- Absorber diameter up to 18 m
- Advanced materials
- 40-50% reduced plot area to 180m x 120 m

Post Combustion Capture – Power plant
Typical process integration option (LB-1)



Post Combustion Capture – Power plant
Advanced process integration option (LB-2)*

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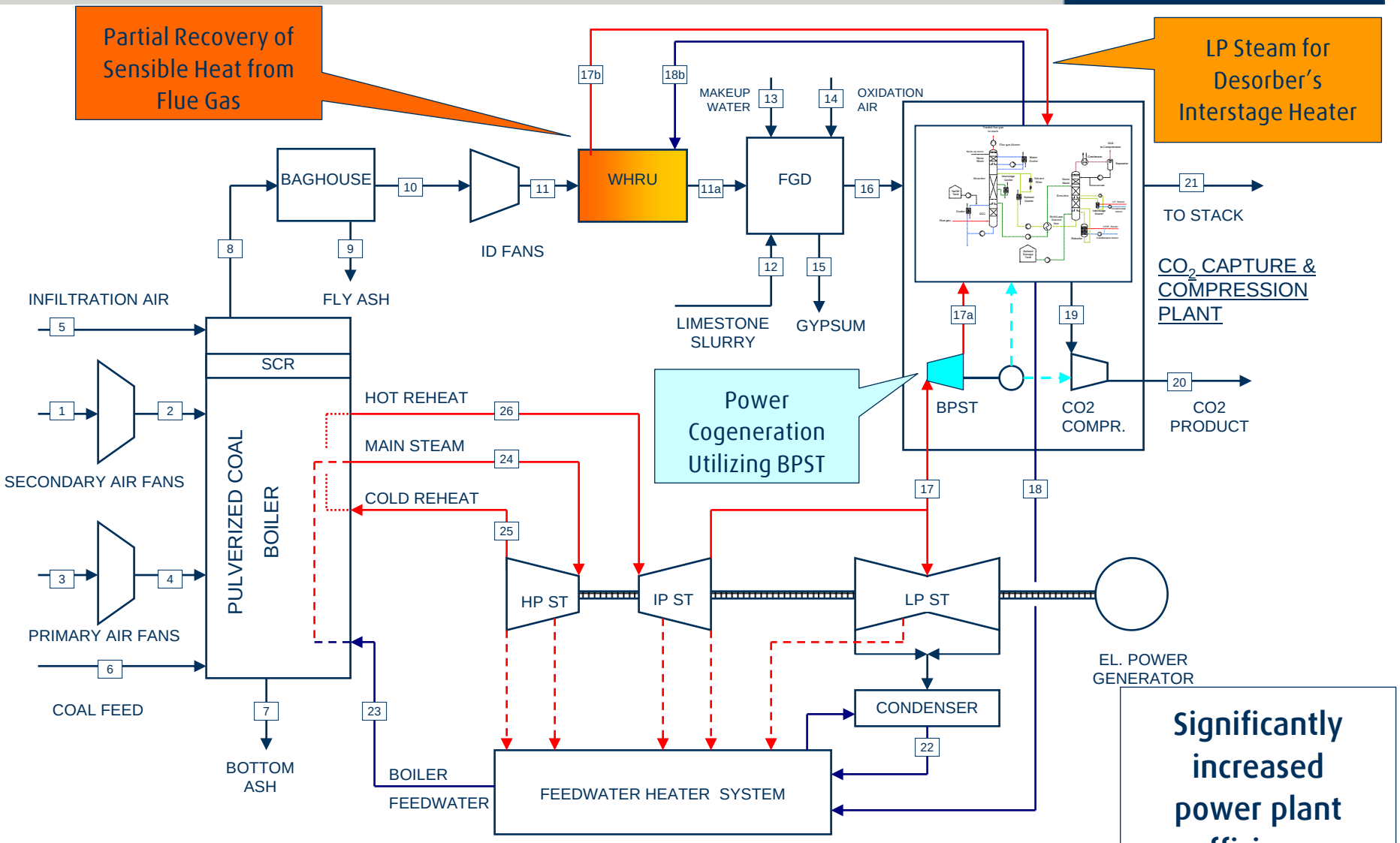
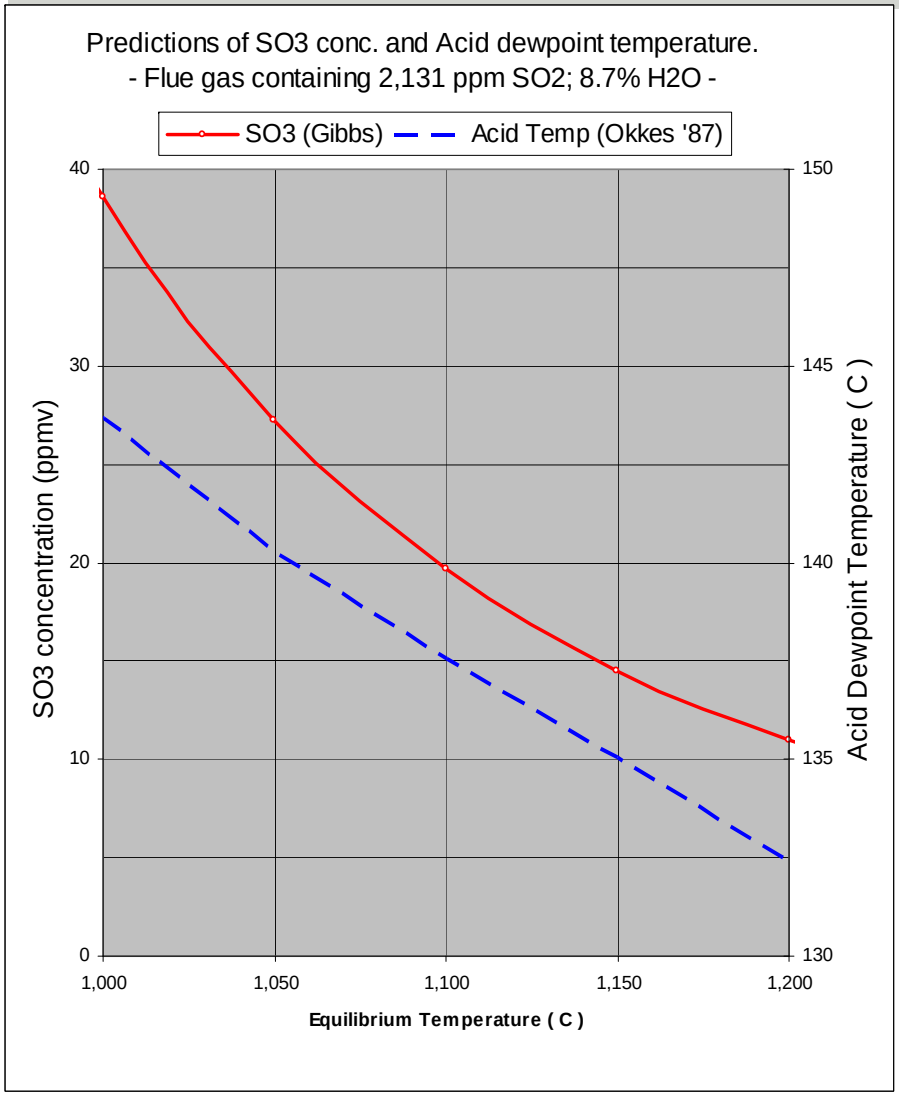
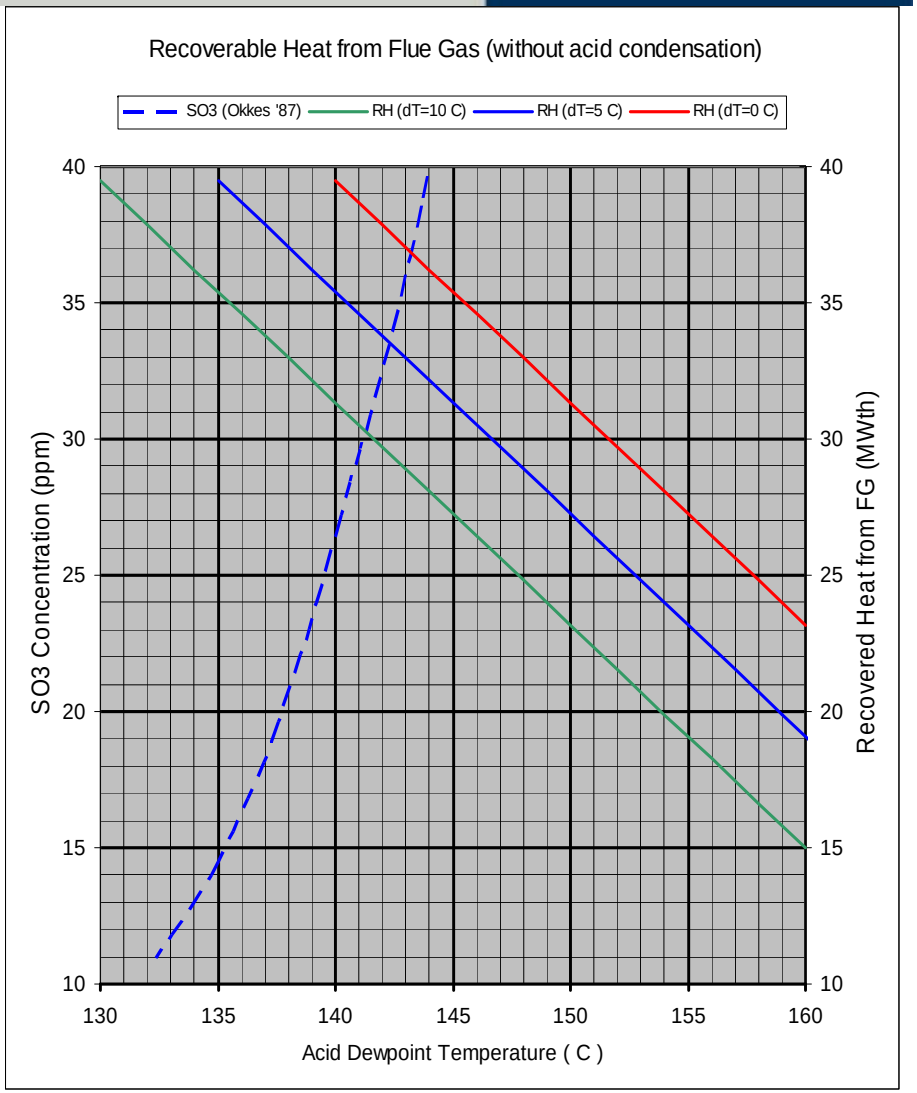


* Concepts covered by Provisional Patent Applications, USPTO, 2012

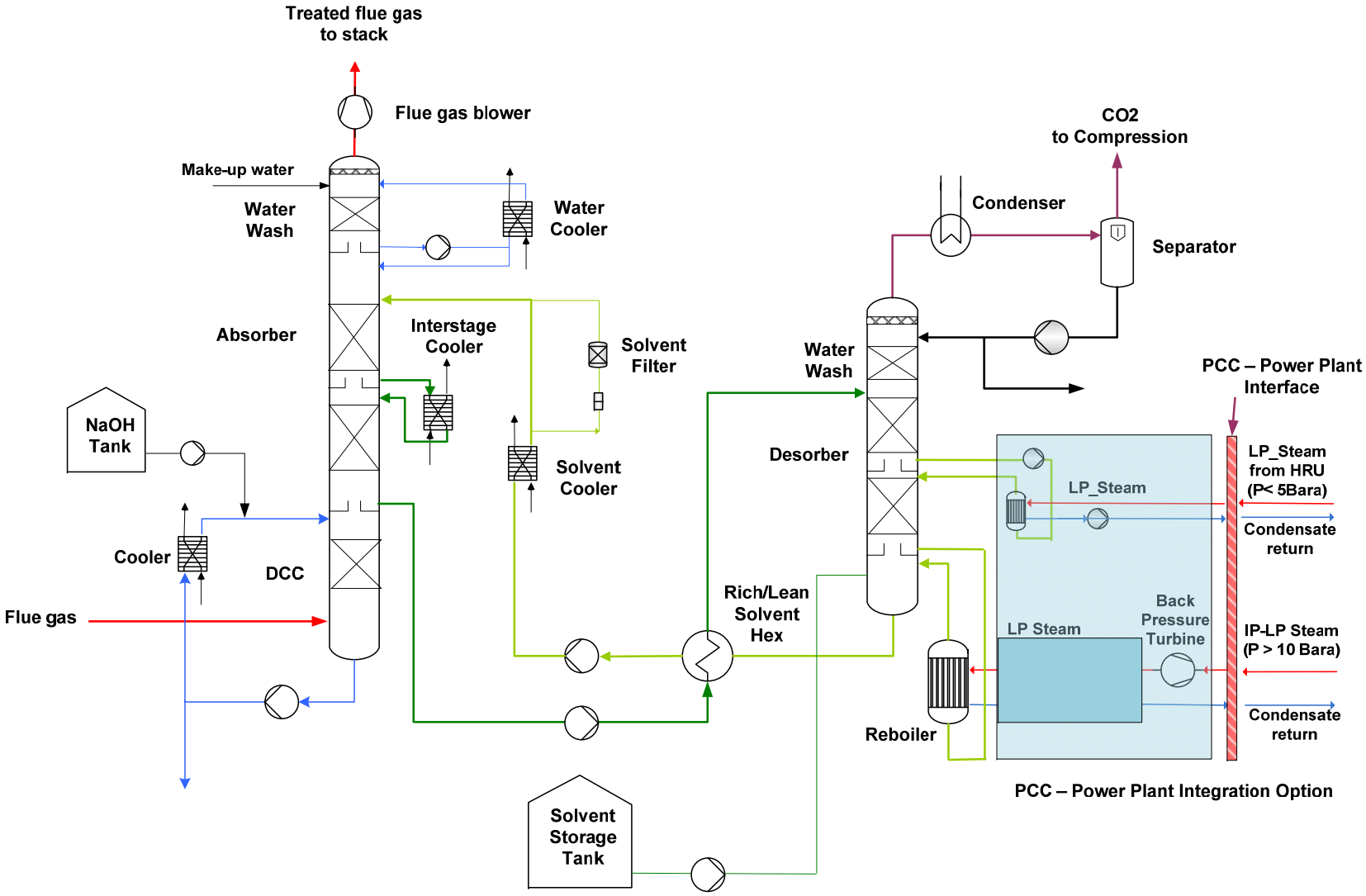
Mitigation of acid dew point condensation issues*





* Okkes A.G., Badger B.V., 1987, "Get acid dew point of flue gas", Hydrocarbon. Processing pp. 53-55.

Post Combustion Capture – Power plant
Advanced process integration option (LB-2)*



* Concepts covered by Provisional Patent Applications, USPTO, 2012

Detailed material and energy balances for 550 MW_e power plant with Linde-BASF PCC (LB-2)

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Stream Number

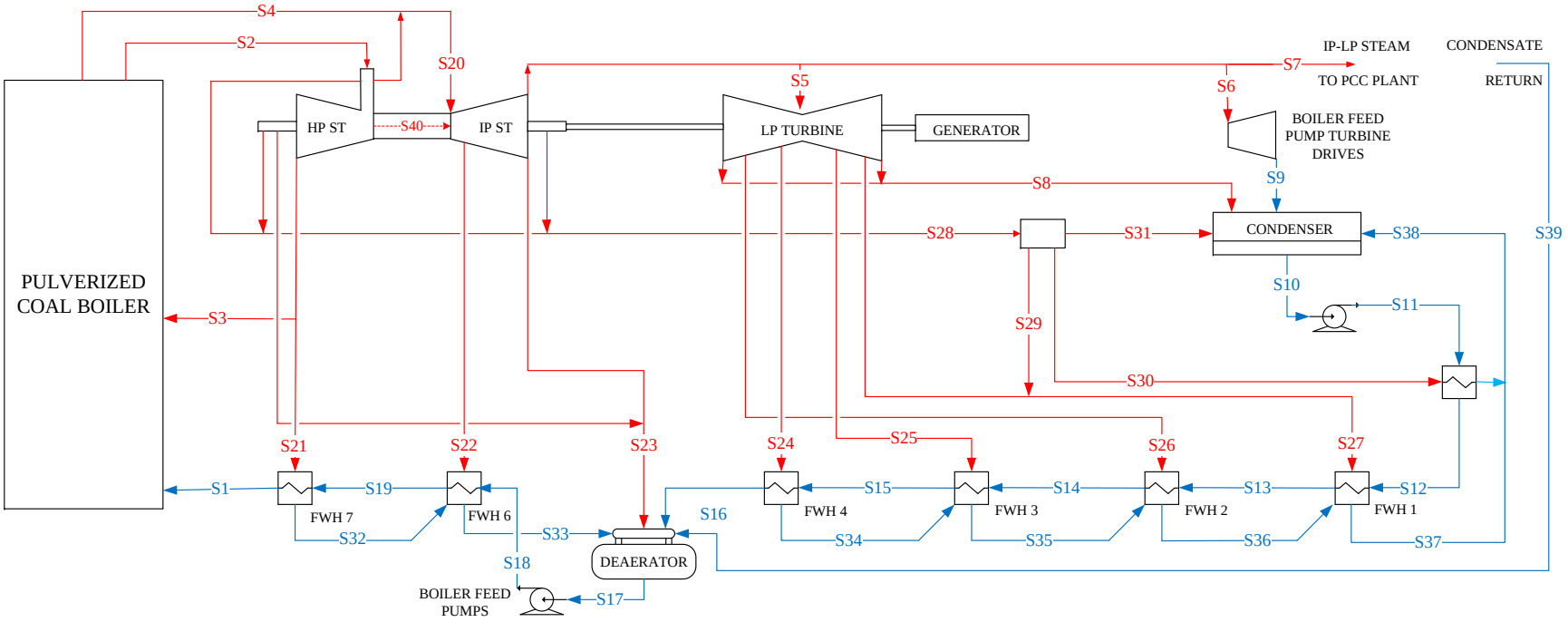
Stream Properties	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Flow (lb/hr)	4,638,326	4,638,326	4,272,476	4,272,476	2,488,797	186,819	1,225,000	2,056,570	186,819	2,683,300	2,683,300	2,683,300	2,683,300	2,683,300	2,683,300
Temperature (F)	484.4	1,050.0	690.4	1,050.0	742.7	742.7	742.7	101.1	126.1	101.1	101.7	102.8	152.4	190.5	257.7
Pressure (psia)	3,100.5	2,414.7	620.5	555.7	167.7	167.7	167.7	1.0	2.0	1.0	400.0	395.0	390.0	385.0	380.0
Enthalpy (Btu/lb)	-6,377	-5,353	-5,502	-5,301	-5,449	-5,449	-5,449	-5,818	-5,756	-6,778	-6,776	-6,775	-6,725	-6,687	-6,620

	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30
Flow (lb/hr)	2,683,300	4,638,326	4,638,326	4,638,326	4,275,677	327,120	213,348	189,558	69,513	162,472	90,728	112,938	7,684	3,366	2,366
Temperature (F)	284.7	363.2	370.8	424.1	1,049.9	687.1	926.2	738.5	529.8	444.5	230.5	162.2	707.8	707.8	707.8
Pressure (psia)	375.0	159.3	3,110.5	3,105.5	555.7	589.7	350.5	159.3	64.2	41.6	11.8	5.0	167.7	167.7	167.7
Enthalpy (Btu/lb)	-6,592	-6,511	-6,499	-6,442	-5,301	-5,502	-5,361	-5,450	-5,549	-5,589	-5,686	-5,731	-5,467	-5,467	-5,467

	S31	S32	S33	S34	S35	S36	S37	S38	S39	S40
Flow (lb/hr)	1,952	327,120	540,468	69,513	231,985	322,712	435,650	438,006	1,225,000	24,183
Temperature (F)	707.8	434.2	380.8	267.7	200.5	162.4	112.8	112.8	367.9	901.6
Pressure (psia)	167.7	359.2	197.7	40.3	11.6	5.0	1.4	1.4	380.0	555.7
Enthalpy (Btu/lb)	-5,467	-6,434	-6,492	-6,610	-6,678	-6,716	-6,766	-6,766	-6,506	-5,381

Total ST Electrical Power:	618.5	MW
Additional BPT El. Power:	25.6	MW
Net Electrical Power:	550.0	MW
Net Efficiency:	29.4	%

Reference state: Vapor Heat of Formation @ 77 F & 14.7 psia



Detailed material and energy balances for 550 MW_e power plant with Linde-BASF PCC (LB-2)

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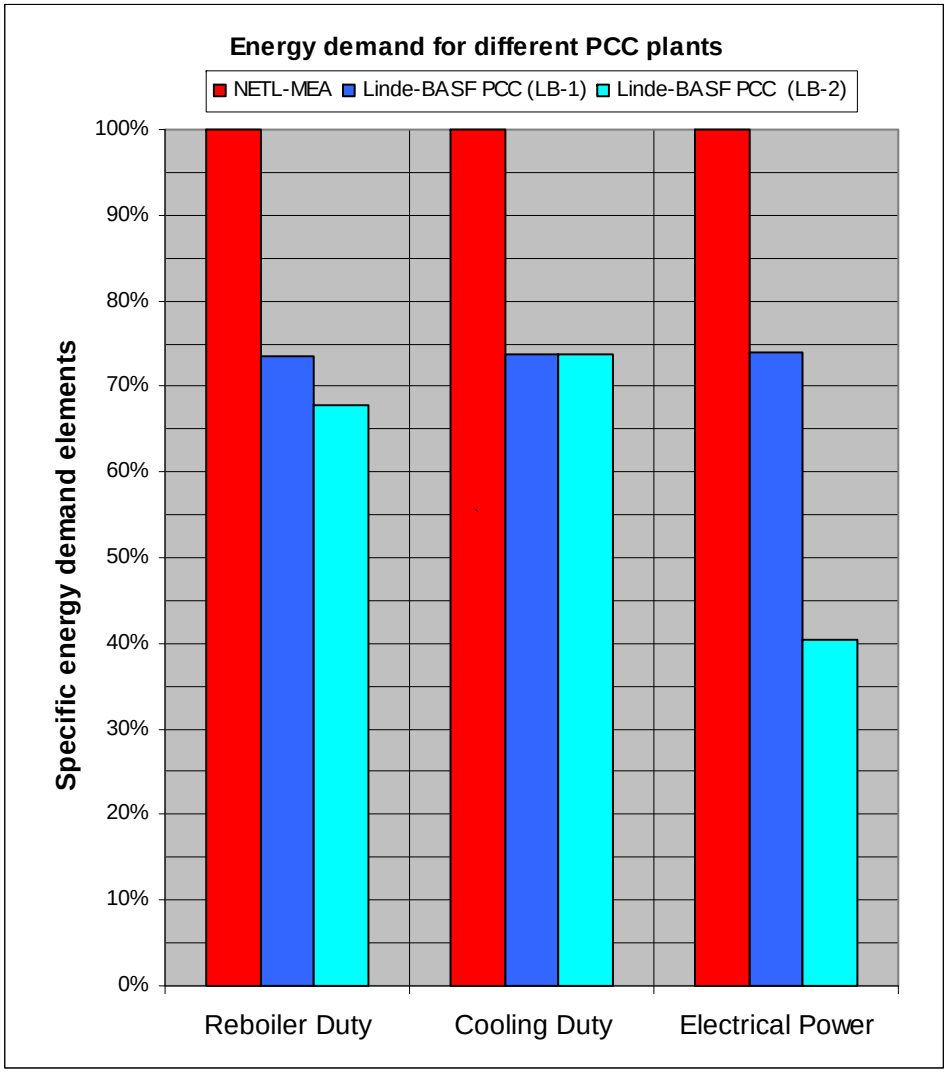
Stream Properties	Stream Number														
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
V-L mol. fract.	1	1	1	1	1	0	0	1	0	1	1	0	0	0	0
Ar	0.0092	0.0092	0.0092	0.0092	0.0092	0.0000	0.0000	0.0087	0.0000	0.0087	0.0087	0.0000	0.0000	0.0000	0.0000
CO2	0.0003	0.0003	0.0003	0.0003	0.0003	0.0000	0.0000	0.1450	0.0000	0.1450	0.1450	0.0000	0.0000	0.0000	0.0000
H2O	0.0099	0.0099	0.0099	0.0099	0.0099	0.0000	0.0000	0.0869	0.0000	0.0869	0.0869	1.0000	1.0000	1.0000	1.0000
N2	0.7732	0.7732	0.7732	0.7732	0.7732	0.0000	0.0000	0.7323	0.0000	0.7323	0.7323	0.0000	0.0000	0.0000	0.0000
O2	0.2074	0.2074	0.2074	0.2074	0.2074	0.0000	0.0000	0.0247	0.0000	0.0247	0.0247	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0021	0.0000	0.0021	0.0021	0.0000	0.0000	0.0000	0.0000
HCl	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	1.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (lbmol/hr)	142,757	142,757	43,853	43,853	3,300	0	0	200,865	0	200,865	200,865	6,970	29,861	2,417	19,775
V-L Flowrate (lb/hr)	4,119,335	4,119,335	1,265,417	1,265,417	95,227	0	0	5,974,752	0	5,974,752	5,974,752	125,559	537,944	69,737	356,244
Solid Flowrate (lb/hr)	0	0	0	0	0	547,917	10,630	42,518	42,518	0	0	54,894	0	0	88,757
Temperature (F)	59	67	59	77	59	59	350	350	350	350	375	59	59	59	130
Pressure (psia)	14.7	15.3	14.7	16.1	14.5	14.7	14.4	14.4	14.4	14.2	15.5	14.7	14.7	14.7	14.7
Enthalpy (Btu/lb)	-41.9	-40.0	-41.9	-37.5	-41.9	-1,565.4	-6,614.7	-1,110.0	-6,614.7	-1,069.9	-1,063.6	-6,820	-6,819.7	-41.9	-6,775.5
Density (lb/ft3)	0.08	0.08	0.08	0.08	0.08	95.20	130.43	0.05	130.43	0.05	0.05	62.36	62.36	0.08	61.47
Molecular Weight	28.86	28.86	28.86	28.86	28.86	8.98	68.53	29.86	68.53	29.75	29.75	18.02	18.02	28.86	18.02

	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S11a	S17a	S17b	S18b
V-L mol. fract.	1	1	0	1	1	1	0	0	1	1	1	0	0	1	0
Ar	0.0081	0.0000	0.0000	0.0000	0.0000	0.0106	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.1349	0.0000	0.0000	0.9925	0.9998	0.0177	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	0.1532	1.0000	1.0000	0.0073	0.0000	0.0464	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
N2	0.6798	0.0000	0.0000	0.0001	0.0001	0.8937	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0240	0.0000	0.0000	0.0000	0.0000	0.0315	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
HCl	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (lbmol/hr)	219,115	67,999	67,999	65,158	26,593	166,674	148,947	257,469	257,469	237,161	237,161	200,865	67,999	6,747	6,747
VL Flowrate (lb/hr)	6,317,527	1,225,000	1,225,000	1,173,830	1,170,275	4,681,265	2,683,300	4,638,326	4,638,326	4,272,476	4,272,476	5,974,752	1,225,000	121,552	121,552
Solid Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88,757
Temperature (F)	130	743	368	68	89	89	102	484	1,050	690	1,050	302	591	284	284
Pressure (psia)	14.7	167.7	380.0	47.9	2,215.0	14.7	400.0	3,100.5	2,414.7	620.5	555.7	15.3	79.8	52.4	53.9
Enthalpy (Btu/lb)	-1,331.3	-5,448.8	-6,505.7	-3,855.6	-3,951.0	-276.0	-6,776.1	-6,376.7	-5,353.2	-5,501.6	-5,300.6	-1,082.3	-5,520.1	-5,671.5	-6,593.4
Density (lb/ft3)	0.07	0.24	54.97	0.38	51.19	0.07	62.03	50.93	2.98	0.98	0.63	0.06	0.13	0.12	57.78
Molecular Weight	28.83	18.02	18.02	18.02	44.01	28.09	18.02	18.02	18.02	18.02	18.02	29.75	18.02	18.02	18.02

Reference state: Vapor Heat of Formation @ 77 F & 14.7 psia; Reference State for Coal and Ash: Solid Heat of Formation @ 77F & 14.7 psia

Specific energy requirements for PCC plant



Reboiler Duty incremental reductions:

- 21.7% by BASF OASE® blue solvent
- 4.8% by Linde-BASF PCC plant design
- 5.6% by heat integration

El. Power incremental reductions:

- 26% by higher reboiler pressure and PCC process optimization
- 33.5% by power cogeneration using BPT

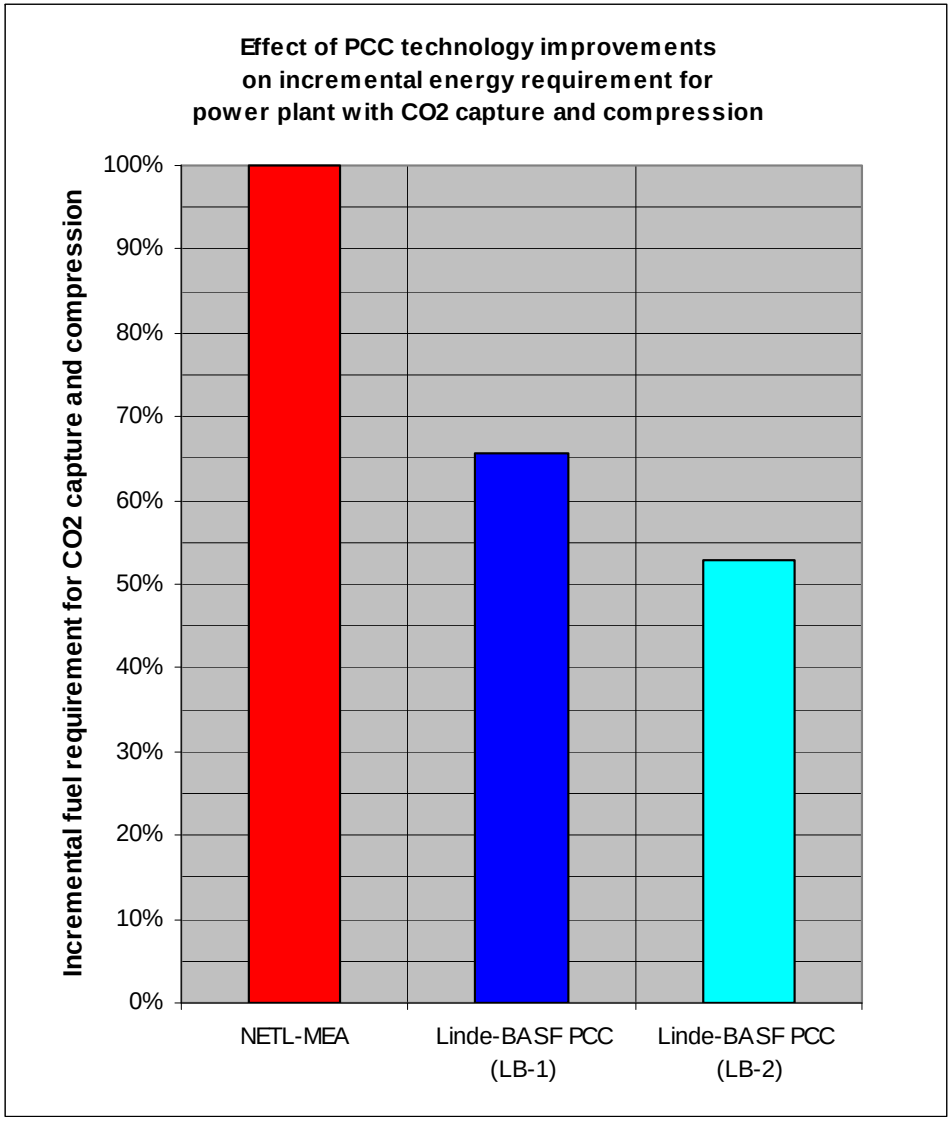
Utility	NETL-MEA	LB-1	LB-2
Reboiler Duty, (GJ/MT_CO_2)	3.55	2.61	2.41*
Cooling Duty, (MW_{th}hr)/(MT_CO_2)	1.64	1.21	1.21
Electrical Power (kW_ehr/MT_CO_2)	119.9	88.7	48.5**

* Effect of interstage heater - recovered heat from flue gas

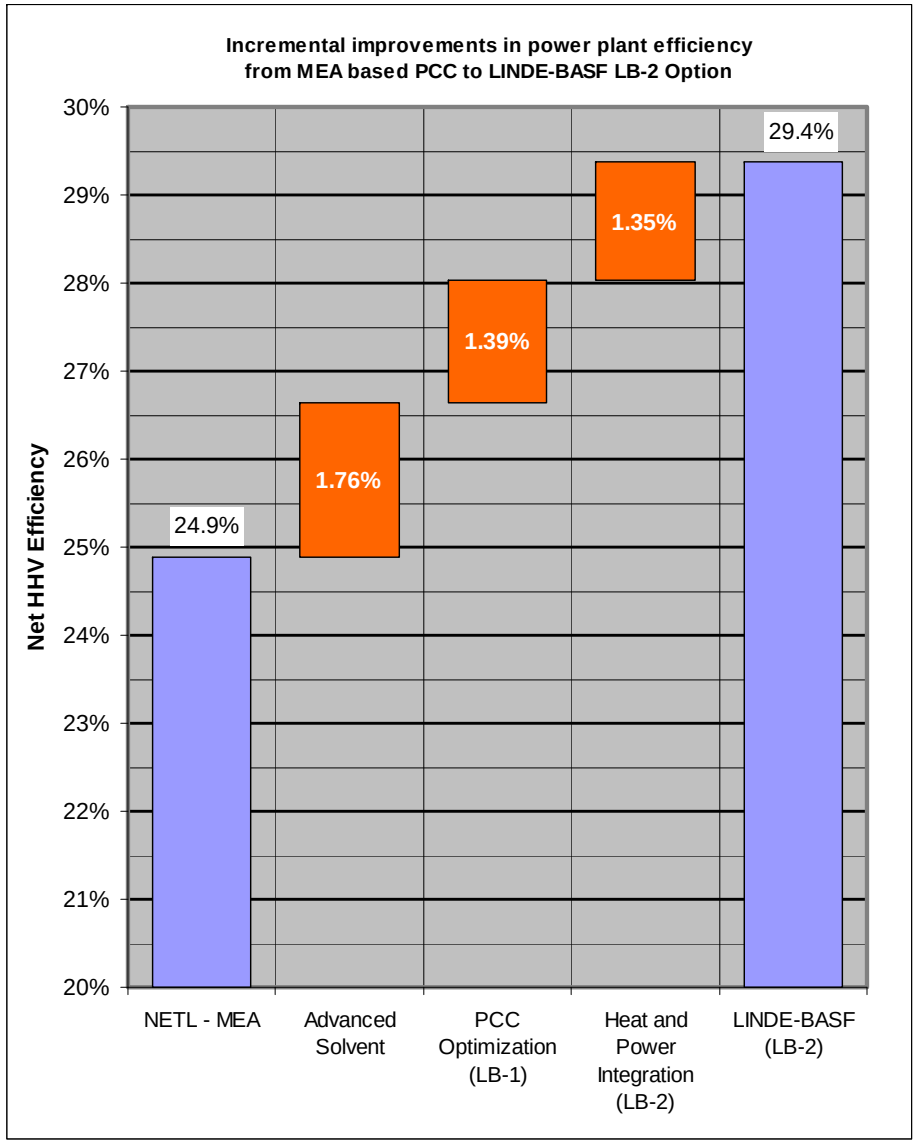
** Effect of power cogeneration from IP-LP steam expansion before used for reboiler

MT - Metric Tonne

Incremental energy reductions for PCC: Linde-BASF vs MEA PCC technology



Incremental power plant efficiency improvements with Linde-BASF PCC technology



Significantly increased power plant efficiency

1. Reduced energy requirements for BASF OASE® blue solvent regeneration
2. Optimized PCC plant design, including
   - — Blower location
   - — Higher regeneration pressure
   - — Optimized operating parameters
3. Efficient heat and power process integration
   - — Sensible waste heat from FG used for enhanced solvent regeneration
   - — Excess excergy from extracted IP-LP steam utilized for power cogen.

Performance Summary:
Linde-BASF LB-1 & LB-2 vs NETL MEA PCC Option

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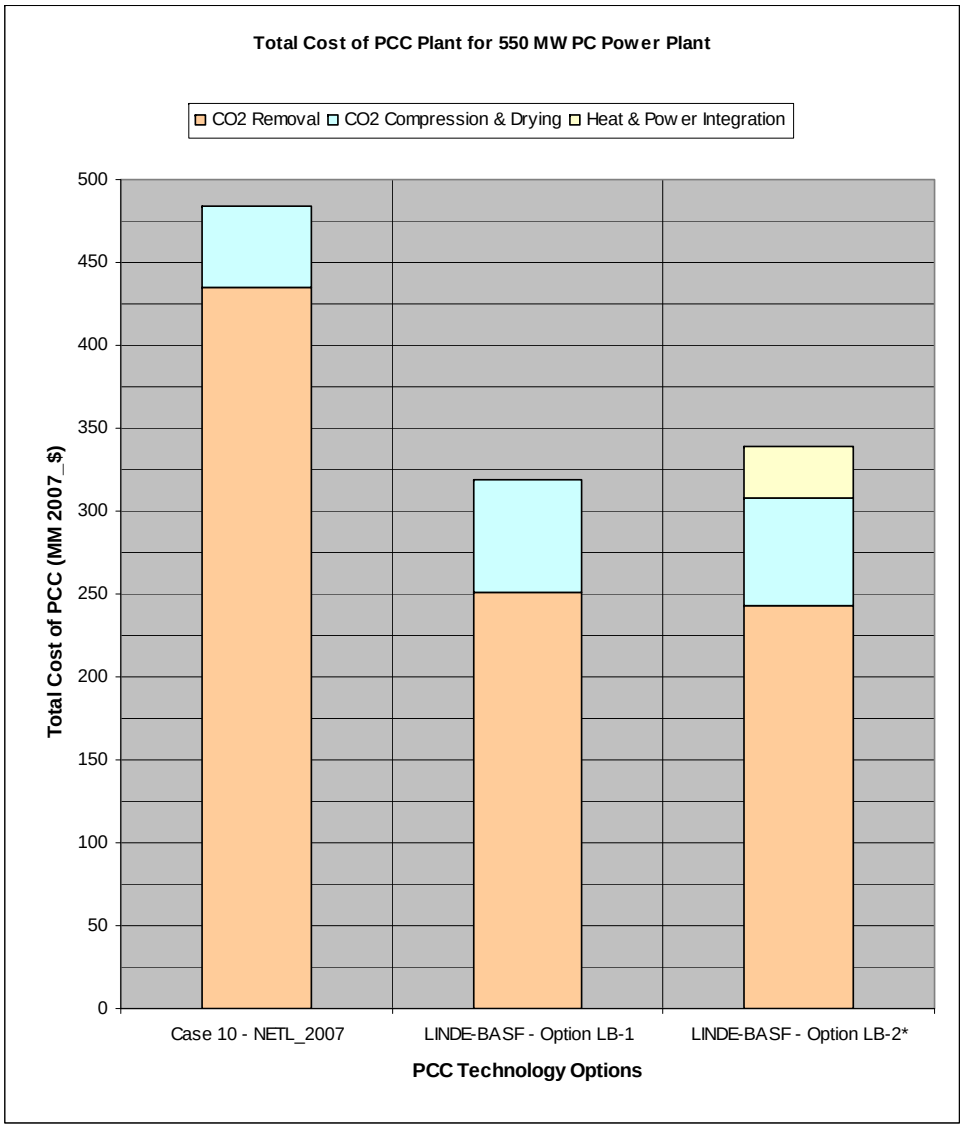
Performance Summary of PC Power Plant with different PCC Options

	NETL_2007 Case 10	LINDE-BASF Case LB-1	LINDE-BASF Case LB-2*
TOTAL (STEAM TURBINE) POWER, kWe	**679,923**	**646,742**	**644,174**
Coal handling and Conveying	520	485	473
Limestone Handling & Reagent Preparation	1,400	1,247	1,189
Pulverizers	4,400	3,911	3,731
Ash Handling	840	748	714
Primary Air Fans	2,060	1,824	1,740
Forced Draft Fans	2,620	2,323	2,216
Induced Draft Fans	11,180	9,924	11,156
SCR	80	75	74
Baghouse	100	100	100
FGD Pumps and Aggitators	4,680	4,161	3,969
Amine System Auxiliary	23,500	11,968	11,416
CO2 Compression	51,610	37,383	35,662
Condensate Pumps	1,210	1,302	1,249
Miscelaneous Balance of Plant	2,000	2,000	2,000
Steam Turbine Auxiliaries	400	400	400
Circulating Water Pumps	14,060	10,958	10,484
Cooling Tower Fans	7,270	5,660	5,416
Transformer Losses	2,380	2,264	2,165
TOTAL AUXILIARIES, kWe	**130,310**	**96,733**	**94,156**
NET POWER, kWe	**549,613**	**550,009**	**550,018**
Net Plant Efficiency (HHV)	24.9%	28.0%	29.4%
Net Plant Heat Rate (Btu/kWh)	13,724	12,194	11,633
CONDENSER COOLING DUTY GJ/h	2,318	2,387	2,291
CONSUMABLES			
Coal As-Received, kg/h	293,288	260,372	248,383
Limestone Sorbent Feed, kg/h	29,010	25,754	21,811
Thermal Input, kWt	2,208,866	1,960,965	1,870,668
Makeup water, m3/min	51.4	40	38

* Total power for LB-2 includes **25.6 MW** generated with BPT (see Exhibits 4-3 & 5-7 for integration option)

Total PCC plant cost



Significantly reduced PCC plant cost

1. Reduced coal combustion (CO_2 production) for 11.1% (LB-1) or 15.2% (LB-2)

2. Single train PCC design with concrete absorber

3. Optimized PCC plant design

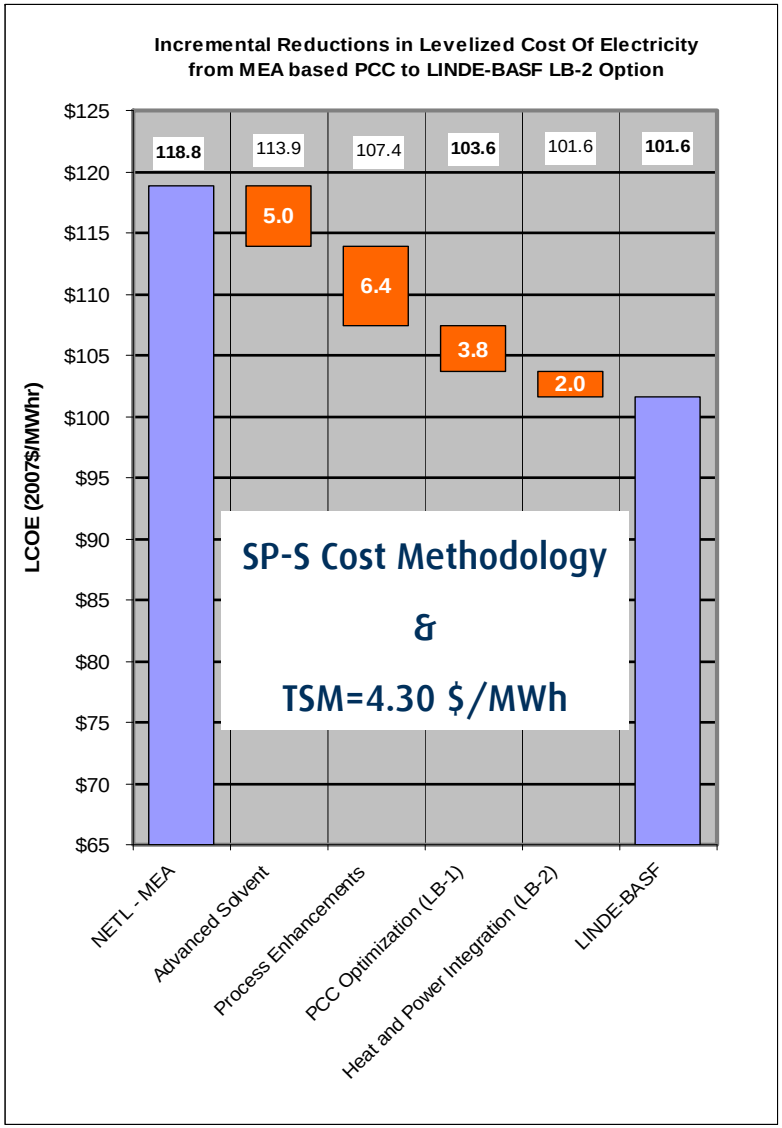
Linde-BASF PCC Total Plant Cost breakdown

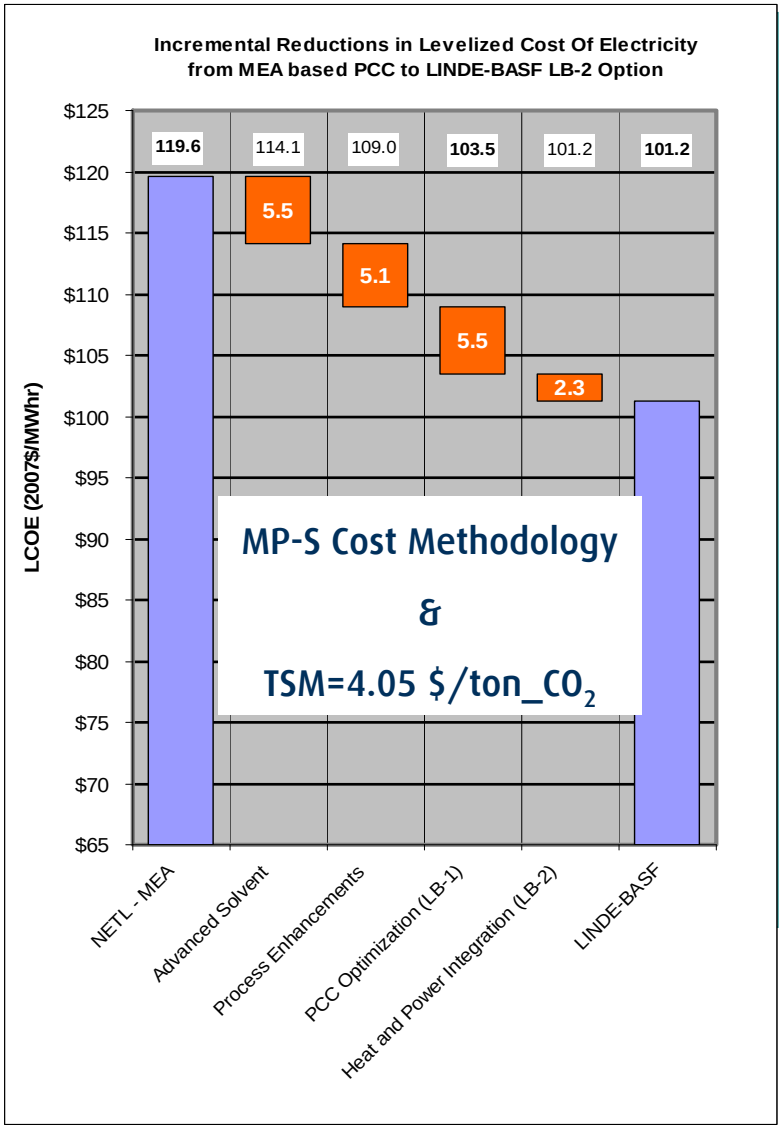
Total Post Combustion Capture Plant Cost details (Millions of 2007$)								
					Contingencies		Total Plant Cost	
	Equipment Cost	Labor Cost	Bare Erect Cost	Eng.CM&Fee Cost	Process	Project	MM$	$/kW
Linde-BASF PCC -LB-1 Option								
CO2 Removal System LB-1	133.535	45.877	179.412	28.593	35.882	7.176	251.063	456.479
CO2 Compression & Drying	43.900	14.745	58.645	4.826	0.000	2.346	65.817	119.666
Total	**177.435**	**60.621**	**238.057**	**33.419**	**35.882**	**9.522**	**316.880**	**576.146**
Linde-BASF PCC - LB-2 Option, with heat and power integration								
CO2 Removal System LB-2	129.201	44.387	173.588	27.664	34.718	6.944	242.914	441.662
Heat and Power Integration	16.304	5.601	21.905	3.491	4.381	0.876	30.653	55.733
CO2 Compression & Drying	42.475	14.266	56.741	4.669	0.000	2.270	63.680	115.782
Total	**187.980**	**64.255**	**252.234**	**35.825**	**39.099**	**10.089**	**337.247**	**613.177**

Itemized Total Plant Cost

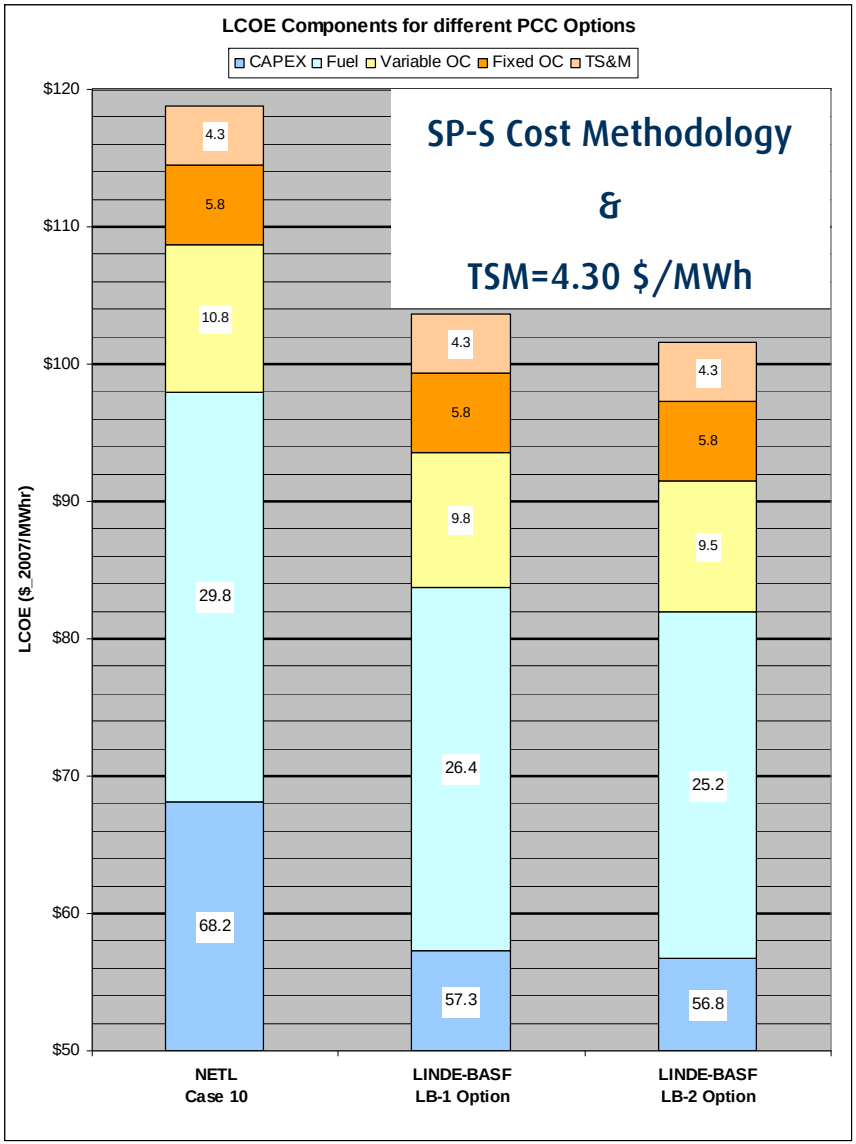
Total Plant Cost (MM 2007_$)						
Scaling Methodology			Single Parameter Scaling		Multiple Parameter Scaling	
Case		NETL_2007 Case 10	LB-1	LB-2	LB-1	LB-2
Acct No.	Description					
1	Coal & Sorbent Handling	48.223			44.809	43.515
2	Coal & Sorbent Prep. & Feed	22.942			21.243	20.601
3	Feedwater & Misc. BOP Systems	100.377			90.210	86.448
4	PC Boiler	333.245			306.863	296.932
5	Flue Gas Cleanup	177.474			163.486	158.219
6A	CO2 Removal	435.391	251.063	242.914	251.063	242.914
6B	CO2 Compression	49.059	65.817	63.680	65.817	63.680
6C	Heat & Power Integration	0.000	0.000	30.653	0.000	30.653
7	HRSG, Duct & Stack	41.551			40.303	39.815
8	Steam Turbine Generator	125.317			112.010	107.140
9	Cooling Water System	65.518			56.339	54.876
10	Ash/Spent Sorbent Handling Sys	15.515			14.533	14.159
11	Accessory Electric Plant	76.384			66.559	63.002
12	Instrumentation & Control	24.056			22.791	22.305
13	Improvements to site	15.210			14.657	14.442
14	Buildings & Structures	61.016			60.551	60.367
	TPC without PCC	1,106.828	1,022.687	990.937	1,014.353	981.821
	PCC Cost	484.450	316.880	337.247	316.880	337.247
	TOTAL PLANT COST	**1,591.278**	**1,339.567**	**1,328.185**	**1,331.233**	**1,319.068**

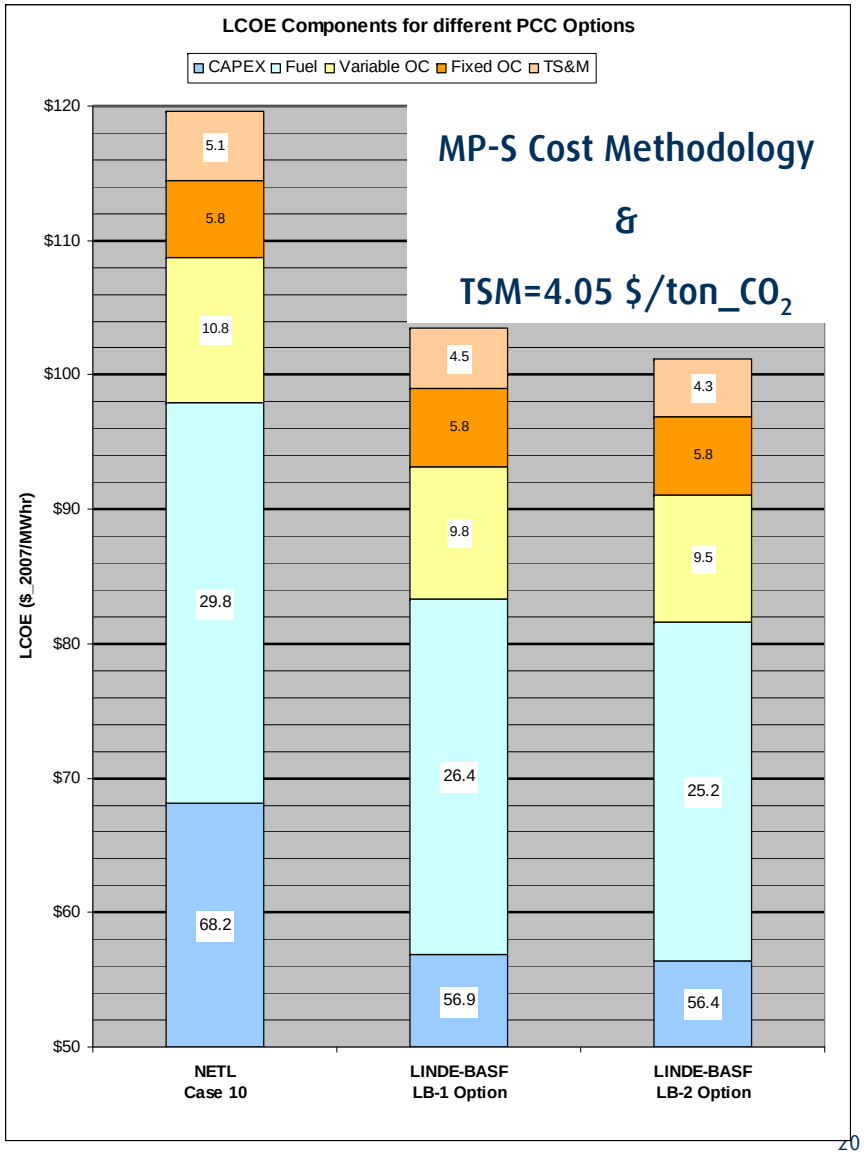
Incremental LCOE reductions with Linde-BASF PCC process options





Comparison of LCOE components





Estimated LCOE variations

Methodology*		LCOE (2007$/MWh)	
TPC Estimates	TSM Calculations	LB-1 Option	LB-2 Option
SP-S	4.30 $/MWh	**103.6**	**101.6**
MP-S	4.30 $/MWh	**103.3**	**101.2**
SP-S	4.05 $/ton_CO2	**103.8**	**101.6**
MP-S	4.05 $/ton_CO2	**103.5**	**101.2**

* SP-S: Single Parameter Scaling; MP-S: Multiple Parameter Scaling - see section 5.3

Conclusions

THE LINDE GROUP

Linde

- Detailed techno-economic evaluation completed for the 550 MWe coal-fired power plant incorporating Linde-BASF PCC technology using rigorous modeling.

- BASF's advanced OASE® blue solvent performance significantly improves power plant efficiency

- Linde-BASF innovative PCC plant design increases power plant efficiency and reduce the levelized cost of electricity
  - 28.0% efficiency and $103.8/MWh for LB-1 versus 24.9% and $118.8/MWhr for the reference case

- Process integration options identified to even further increase power plant efficiency and reduce the levelized cost of electricity
  - 29.4% efficiency and $101.6/MWh for LB-2 versus the reference

- The planned slipstream pilot plant testing will further validate several of the key features confirming the power plant efficiency increase and cost of electricity decrease