SLIPSTREAM PILOT-SCALE DEMONSTRATION OF A NOVEL AMINE-BASED POST-COMBUSTION TECHNOLOGY FOR CARBON DIOXIDE CAPTURE FROM COAL-FIRED POWER PLANT FLUE GAS

Topical Report:

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

December 1, 2011 - May 4, 2012

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WORK PERFORMED UNDER AGREEMENT
DE-FE0007453

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Acknowledgement:

This presentation is based on work supported by the Department of Energy under Award Number DE-FE0007453.

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Executive Summary

This topical report presents the techno-economic evaluation of a 550 MWe subcritical pulverized coal (PC) power plant utilizing Illinois No. 6 coal as fuel, integrated with a Linde-BASF post-combustion CO_2 capture (PCC) plant incorporating BASF's OASE® blue aqueous amine-based solvent. The process simulation and modeling is performed using Honeywell's Unisim process flowsheet simulator. Details of the PCC plant are modeled using Bryan Research and Engineering's Promax® software and BASF's proprietary thermodynamic and process models. The model developed is first validated by reproducing the results of DOE/NETL Case 10 representing a 550 MWe subcritical PC-fired power plant with post-combustion capture incorporating a monoethanolamine (MEA) solvent as a reference case.

The results of the techno-economic assessment are shown comparing two specific options utilizing the BASF OASE® blue solvent against the DOE/NETL reference MEA case. The results are shown comparing the energy demand for post-combustion CO_2 capture, the incremental fuel requirement, and the net higher heating value (HHV) efficiency of the PC power plant integrated with the PCC plant. A comparison of the incremental capital cost for the PCC plant corresponding to a net 550 MWe power generation is also presented. A levelized cost of electricity (LCOE) assessment is shown illustrating the substantial reduction achieved with the Linde-BASF PCC plant compared to the reference MEA plant. The key factors contributing to the reduction of LCOE, and the magnitude of reduction achieved by each of these factors, are also shown.

The net efficiency of the integrated PC power plant with CO_2 capture is increased from 24.9% with the reference MEA plant to between 28.0% and 29.4% with the Linde-BASF PCC plant incorporating the BASF OASE® blue solvent, based on the specific option considered. The Linde-BASF PCC plant also results in significantly lower overall capital costs, thereby reducing the LCOE from 118.8 mills/kWh for the reference MEA plant to between 101.2 and 103.8 mills/kWh with the Linde-BASF PCC plant incorporating the BASF OASE® blue solvent, based on the specific option.

1. Introduction

This topical report, prepared in accordance with the DOE requirements, consists of an executive summary, six sections and five appendices. While Section 2 briefly outlines the evaluation basis used in this study, including the methodology of calculating the LCOE; Section 3 is divided into two subsections: the first provides background information related to the development of the BASF OASE® blue solvent technology, while the subsequent subsection provides a simplified process flow diagram of the Linde-BASF advanced PCC technology and highlights the major innovations incorporated into the design of a PCC plant.

Section 4 starts with a block flow diagram of an integrated power plant with PCC with a brief description of the overall process and then provides key assumptions used in this study. The process integration options considered between a PC power plant and Linde-BASF PCC plant are also illustrated.

Section 5 provides the detailed results of the techno-economic assessment. After highlighting the modeling approach and the methodology adopted for its validation, the performance results of a 550 MWe subcritical PC power plant integrated with the Linde-BASF PCC plant are presented. Two PCC process configurations are presented in more detail:

- LB-1 option, representing Linde-BASF PCC plant with optimized configuration and operating parameters, and
- LB-2 option, which explores optional integration of waste heat recovery and power cogeneration for internal PCC heat and power requirements.

The performance indicators include comparisons of specific energy requirements for Linde-BASF PCC options versus reference Case 10 of DOE/NETL_2007 study (reference [1]) and demonstrate the superior performance of the proposed technology. This section also provides detailed material and energy balances for the overall integrated PC power plant equipped with PCC, as well as of the water-steam-power generation island of the plant. The performance summary details all elements of auxiliary power consumption along with net plant efficiencies, and also highlights all major environmental benefits of the Linde-BASF PCC technology.

Evaluation of the resulting LCOE for a 550 MWe PC power plant equipped with PCC starts with a presentation of the methodologies used to estimate the total plant cost for the PCC plant, and for an integrated PC power plant with PCC. The incremental reduction in LCOE values when progressively advanced PCC technology options are used, instead of MEA-based PCC technology explored in the DOE/NETL base study [Ref. 1], is quantified.

The techno-economic report is completed with concluding remarks emphasizing the benefits of the proposed Linde-BASF advanced PCC technology integrated with a large-scale PC power plant.

2. Evaluation Basis

Honeywell UniSim Design software has been used in this study as a generalized platform for rigorous mathematical modeling, simulation, design, and optimization of the integrated PC power plant equipped with a PCC unit. Bryan Research and Engineering's ProMax® and BASF's proprietary packages have been utilized for the detailed modeling, analysis, and optimization of the amine-based PCC plant options. The resulting key process performance indicators have been used to determine the incremental capital charges for the power plant (with respect to the reference Case 10 of DOE/NETL Study (Ref. [1])) by utilizing estimated scaling parameters, while the capital cost estimate for the Linde-BASF PCC technology is based on in-house proprietary costing tools and recent experience from proposals and studies.

A previously developed Linde thermodynamic model for solid fuels, consistent with UniSim computational platform, has been used in this study to reproduce thermodynamic and physical properties of Illinois No. 6 bituminous coal shown below.

Exhibit 2-1. Design Coal

Rank	**Bituminous**	
Seam	**Illinois No. 6 (Herrin)**	
Source	**Old Ben Mine**	
Proximate Analysis (weight %)		
	As Received	**Dry**
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Sulfur	2.51	2.82
HHV, kJ/kg	27,113	30,506
HHV, Btu/lb	11,666	13,126
LHV, kJ/kg	26,151	29,544
LHV, Btu/lb	11,252	12,712

Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	11.12	0.00
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
Ash	9.70	10.91
Oxygen	6.88	7.75
Total	100.00	100.00

Site characteristics, raw water usage, and environmental targets are identical to those detailed in paragraph 2 of the DOE/NETL report [Ref. 1]

The methodology for calculating the cost of electricity levelized over a period of 20 years used in this study is, again, identical as in the DOE/NETL report [Ref. 1]:

$$LCOE = \{(CCF)(TPC) + \Sigma [(LF_{Fi})(OC_{Fi})] + (CF) \Sigma [(LF_{Vi}*OC_{Vi})] \} / [(CF)(aMWh)]$$

Interpretation of all abbreviations is provided in the appendix.

The following economic parameters are used for LCOE calculations:

Capital Charge Factor	=	0.1750
Coal Levelization Factor	=	1.2022
General O&M Levelization Factor	=	1.1568

The economic assumptions used to derive the above values are summarized in Exhibit 2-14 and Exhibit 2-15 of DOE/NETL-2007 study [Ref. 1]. Consequently, the calculated LCOE values in this study have been expressed in 2007$ to be able to consistently evaluate the influence of the novel PCC technology on incremental reduction of LCOE, as compared to DOE/NETL-2007 study.

3. BASF-Linde Post Combustion Capture Technology

The proposed advanced PCC technology is a result of BASF's comprehensive R&D efforts since 2004 in developing advanced amine-based solvents for efficient CO_2 recovery from low-pressure, dilute flue gas streams from power plants and industrial processes, combined with the joint Linde/BASF collaboration since 2007 in designing and testing resulting advanced PCC technology. This section provides the highlights of the key characteristics of BASF's OASE® blue process, along with Linde-BASF PCC plant design innovations.

3.1. BASF OASE® Blue Technology

With climate change becoming an increasing concern globally, BASF’s gas treatment team is actively leveraging its expertise to become a leading contender in the race to make carbon capture and storage (CCS) commercially viable. Over the years, BASF’s gas treatment portfolio has continuously expanded. Beyond extensive offering in technology and gas-treating chemicals, the world’s largest chemical company can supply additional technical support services, such as customized onsite training of its customers’ personnel on the optimized operations of gas treatment processes and equipment. It recently began marketing its entire portfolio under the trade name OASE® with OASE® blue being the brand for flue gas carbon capture. The team considers CCS as the most-effective measure in the mid-term to combat further increase of CO_2 in the atmosphere. Based on over 250 gas treatment reference plants in 2004 in ammonia and oxo-syngas, in natural gas and liquefied natural gas applications, but also experiences in iron ore gas and selective sulfur gas treatment; it was decided at that time to systematically develop new solvents targeting the specific requirements of large-scale carbon capture applications. Besides low pressure and large volume systems, which need to consider emissions to meet environmental requirements, there is the challenge of very low driving forces for CO_2 mass transfer. The oxygen-containing atmosphere is aggressive to amines and energy efficiency will be decisive for the success of such a process. Consequently, the most important parameters for the development were energy demand, cyclic capacity, solvent stability, reactivity, volatility, environmental sustainability, and availability.

BASF's screening procedure comprised over 400 substances, which were pre-selected based on molecular weight, vapor pressure, alkalinity, and safety data. About half of the candidates were further investigated in the labs regarding vapor-liquid equilibrium, reaction kinetics, and stability. About 20 component mixtures were then subject to a proof-of-concept run in BASF's mini plant where the complete capture process is verified. This valuable tool can show in an early development stage whether a process chemical has a potential for further tests at the pilot-scale on real power plant off gases.

In parallel, BASF monitored the energy industries' approaches towards carbon capture and also contributed to several research projects within the 6^{th} and 7^{th} integrated framework programs of the European Union. During the CASTOR and CESAR projects, the BASF team exchanged experiences with the relevant players in the community and transferred significant gas treating know-how from the petrochemical industry to the energy industry and related institutes.

Together with Linde, BASF is a partner in a pilot project steered by RWE Power at German energy provider's Coal Innovation Center in Niederaussem, Germany, near Cologne. The post-combustion pilot plant on coal-fired off gas in Germany was constructed, commissioned, and started-up in 2009. Despite the rather small dimensions and a capacity to capture only 7.2 tonnes of CO_2 per day from a flue gas slipstream of the power plant, several critical issues were successfully tested. In particular, reliable data on energy consumption and long-term stability were generated, which will serve as a basis for this project.

Based on this work and the invaluable feedback of know-how from over 300 plants operating with OASE® technology, BASF can already guarantee performance at today's state-of-development. Guaranteed parameters are capture rate, capacity, reboiler duty, process emissions, circulation rate, and CO_2 purity. Today, an OASE® blue process can be operated reliably to achieve the main objectives. Nevertheless, the technology offers further potential for process optimization and cost reduction to be addressed in this project.

3.2. Post Combustion Capture Plant

The PCC plant is designed to recover 90 percent of the CO_2 contained in the flue gas downstream of the flue gas desulfurization (FGD) unit, purify it (> 99.9 vol% CO_2, < 10 vol. ppm O_2), dehydrate it (dew point temperature: -40 ^oF (40 ^oC)), and compress it to 2,215 psia (15.3 MPa). The major sections of the PCC plant are: Direct Contact Cooler (DCC) with sulfur dioxide (SO_2) Polishing Scrubber, CO_2 Absorber with Intercooler, Water Wash unit, Solvent Stripper with Interstage Heater, and CO_2 Compression and Drying. The design and operation of these PCC plant components, along with options for PC power plant integration, are described in more detail below.

A simplified process flow diagram of the proposed PCC plant is shown in Exhibit 3-1. It is utilizing BASF OASE® blue technology with a series of advanced equipment and process design options incorporated into the Linde-BASF PCC plant design with an ultimate goal of minimizing the energy requirements for CO_2 recovery and compression. A couple of noticeable process configuration variations and improvements include integrated DCC, Absorber and Water Wash units, as well as a flue gas blower located downstream of the absorber and water wash units, which is discussed below in more detail, along with other process integration and optimization options outlined in Section 4.3.

Direct Contact Cooler with SO_2 Polishing Scrubber

As illustrated in Exhibit 3-1, the novel Linde-BASF PCC design fully integrates the DCC unit with the Absorber and Wash units within a common tower. The DCC has a dual function: (1) cool down the incoming flue gas stream to a temperature suitable for efficient CO_2 absorption; and (2) reduce the SO_2 concentration to as low level as possible, to minimize solvent degradation due to the formation of SO_2-amine complexes, by utilizing an aqueous solution of sodium hydroxide (NaOH).

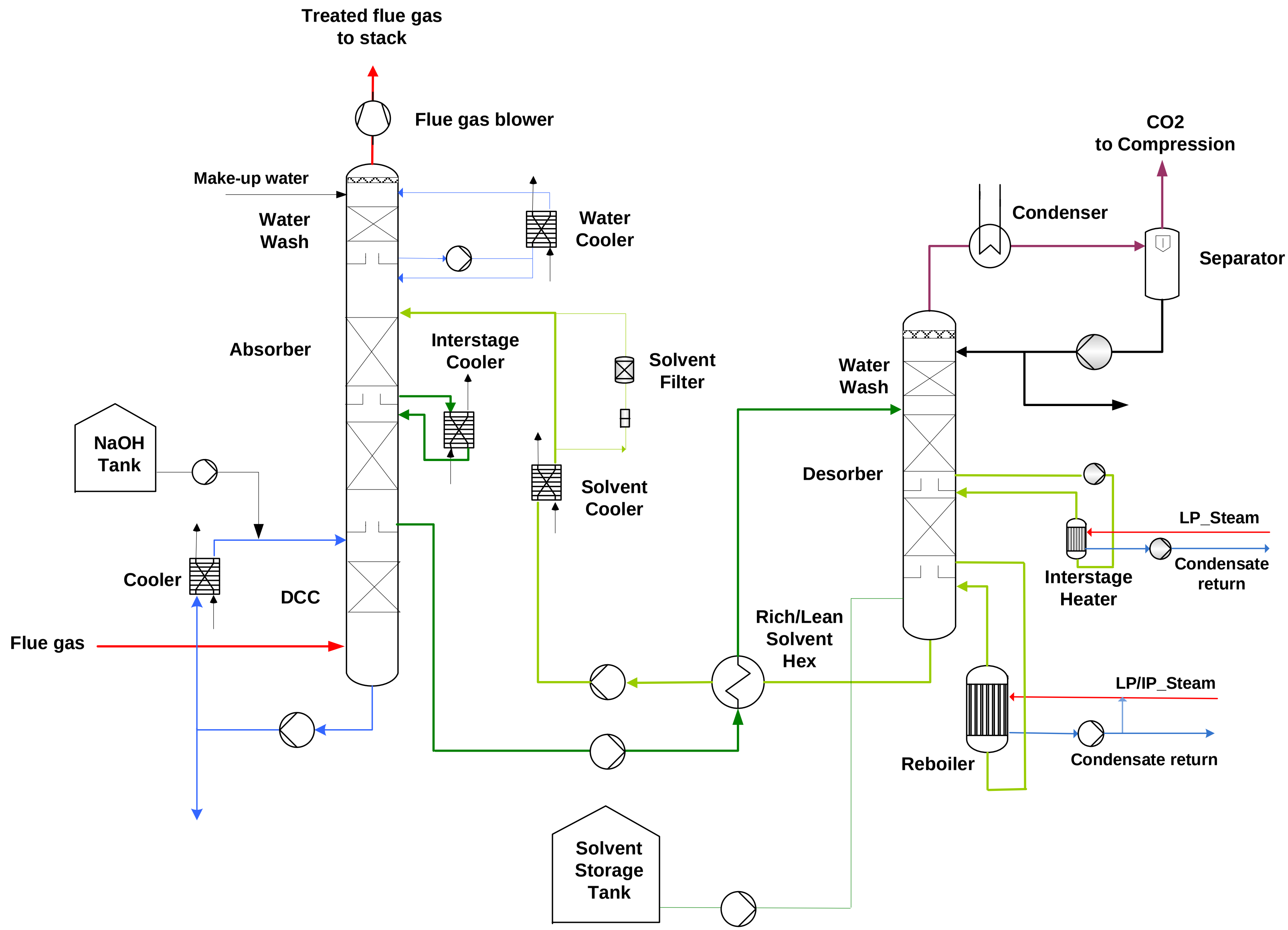


Exhibit 3-1 Simplified Process Flow Diagram of LINDE-BASF Advanced Post Combustion Capture Technology

The feed stream to the PCC plant is water-saturated flue gas from the FGD unit, typically at atmospheric pressure and a temperature of 120 to 140^oF (approximately 50-60^oC). An aqueous solution of NaOH is injected into the water-NaOH circulation loop, and then sprayed at the top of the DCC unit. More than 90% of the incoming SO_2 is scrubbed from the vapor-phase via counter-current contact of the chilled aqueous NaOH solution with warm flue gas. The liquid from the bottom of the DCC bed is fed to a circulating pump; the excess water, condensed from the flue gas, along with dissolved Na_2SO_3, is withdrawn from the loop and sent to an acid neutralization and water treatment facility; while the majority of the aqueous NaOH solution in the recirculation loop is cooled with water. In the case of PC power plants, an integrated cooling water system is used to supply cooling water to all process units, including the PCC and CO_2 compression plants.

The following benefits are derived from the proposed configuration of directly-connected DCC and Absorber units, along with the flue gas blower positioned downstream of the absorber column.

- Significantly reduced cooling duty requirements (~20%), since it is not necessary to cool down the flue gas stream beyond the CO_2 absorption requirements, as is normally done to compensate for a significant temperature rise (up to 30°F) across the flue gas blower.

- Significantly reduced make-up water requirements for the PCC plant (~22%), due to the reduced water removal from the flue gas caused by reduced cooling within the DCC unit.

- Noticeable reduced flue gas blower duty requirement (~13%), due to the substantially lower molar flowrate of flue gas downstream of the absorber, as compared to the flue gas flow upstream of the absorber - the difference being 90% absorbed CO_2 from the flue gas within the absorber bed.

CO_2 Absorber with Interstage Cooler

The CO_2-lean BASF OASE® blue amine-based solvent solution flows down through the absorber bed and efficiently absorbs CO_2 from the flue gas, which flows from the bottom to the top of the column and further to the water wash unit. Since the exothermic chemisorption reaction of CO_2 with amine-based solvents increases the temperature of the flue gas and consequently reduces the equilibrium content of CO_2 in the liquid-phase, it is of utmost importance to maintain a low, relatively constant temperature throughout the entire absorber. In addition to cooling the CO_2-lean amine solvent solution within an external cooler before it is injected to the top of the absorber, a significant solvent temperature rise within the column can be efficiently suppressed by utilizing an interstage cooler, as shown in Exhibit 3.1. Linde's patent-protected, gravity-driven interstage cooler design eliminates the need for an external interstage cooler pump and consequently leads to a simplified design, as well as a reduced capital cost for the absorber with interstage cooler.

The Linde-BASF PCC technology also utilizes the most advanced structured packing for the absorber to promote efficient hydraulic contact of gas and liquid phases, which along with increased CO_2 reaction rates with BASF's OASE® blue solvent, facilitates a fast approach to equilibrium CO_2 concentration in the liquid-phase. Consequently, the capacity of the absorber is significantly increased, this being one of the most critical parameters for a large-scale CO_2 absorption plant. In addition, the advanced structured packing reduces the pressure drop across the column, which in turn leads to reduced flue gas blower requirements. The structured packing selection has been based on optimization of different structured packing offering higher capacities, while trading off on the mass-transfer efficiency.

Water Wash Section

An efficient reduction of the solvent losses and related reduction in the environmental emissions could be achieved by utilizing the water wash section positioned above the absorber bed. The flue gas with depleted CO_2 content that leaves the absorber bed still carries a small amount of solvent. Cold water, sprayed at the top of the wash unit, effectively scrubs the solvent from the flue gas, which is enhanced by significantly reduced equilibrium composition of the solvent components in the vapor-phase caused by the reduced outlet temperature. An external plate and frame cooler in the water recirculation loop transfers the required cooling duty from the cooling water supplied by the central cooling water system.

Solvent Stripper with optional Interstage Heater

The CO_2-rich solvent, previously heated up in the rich/lean heat exchanger, is injected at the top of the solvent stripper column section consisting of two packed beds. The reboiler at the bottom of the stripper column uses the heat of condensation of low-pressure steam to vaporize CO_2 and water from a concentrated solvent, which is directed to the lean/rich solvent heat exchanger. Counter-current flow of the CO_2-rich liquid-phase from the top of the stripper, and the solvent-depleted vapor-phase rising from the reboiler, leads toward separation of the CO_2 and solvent at the top and the bottom of the stripper. A small fraction of carried solvent from the top of the stripper bed is removed from the CO_2 stream in the wash section positioned above the stripper bed. The CO_2 stream saturated with water is significantly cooled in the condenser. Its vapor phase, containing more than 95% of CO_2, is separated from the liquid-phase inside the separator and is routed to the CO_2 compression section, while condensed water is recirculated back to the top of the wash section. Depending on the operating condition, a surplus of condensed water could be re-routed to the absorber, or discharged to the water treatment facility.

The most energy-intensive aspect of amine-based CO_2 capture is low-pressure steam consumption within the reboiler for solvent regeneration. BASF's OASE® blue advanced amine-based solvent significantly reduces energy demand for solvent regeneration, and consequently increases the power plant efficiency and ultimately decreases the cost of produced electricity, as it will be discussed and illustrated in Section 4.

The Linde-BASF advanced PCC technology also incorporates an option to heat the solvent within the stripper by employing an interstage heater. The heater can use lower-temperature steam than the reboiler, and thus reduce demand for the LP steam typically extracted from the steam turbines, which ultimately leads to higher efficiencies in power plants equipped with PCC units. Related process integration with heat recovery options for the interstage heater are discussed in more detail in Section 4.3

Balance of Plant

The remaining process elements of the PCC plant design, including lean/rich solvent heat exchanger; lean and rich solvent circulating pumps; lean solvent cooler- makeup supplies of solvent, NaOH and water; as well as utility filters remain the same as for typical, commercial CO_2 recovery plant configuration.

Heat and power management and its integration with a PC power plant are discussed in more detail in Section 4.3

4. PC Power Plant with CO_2 Capture

This study evaluates a single reheat, subcritical cycle, 550 MWe PC power plant with CO_2 capture, with the basis of design identical to those used for Case 10 of the DOE/NETL-2007 study (Ref. [1]). Only brief process highlights and major assumptions used in this study are presented below.

4.1. Brief Process Description

Exhibit 4-1 highlights the major process units and streams of a PC power plant integrated with a PCC unit. Coal (stream 6) and primary air (streams 3 & 4) are introduced into the boiler through the wall-fired burners. Additional combustion air (streams 1 & 2) is provided by the forced draft fans, while a small amount of ambient air, which leaks into the boiler due to slightly sub-atmospheric pressure, is accounted for by stream 5.

Flue gas from the boiler, after passing through the selective catalytic reduction (SCR) unit for nitrogen oxides (NOx) control and air pre-heater (stream 8), enters a baghouse for fly ash removal (stream 9). Induced draft fans force flue gas flow (stream 11) into the FGD unit for the removal of SO_2, before it is introduced to the PCC plant (stream 16), which is described in more detail in Section 3. A low-pressure steam supply (stream 17) required for the PCC reboiler duty is extracted from the intermediate- to low-pressure (IP-LP) steam turbine crossover pipe as shown in Exhibit 4-1. The condensate (stream 18) from the PCC is returned to the feedwater heater system. The PC boiler produces main steam (stream 24) by boiling and superheating feedwater (stream 23), and also reheats exhaust stream (stream 25) from the high-pressure turbine to produce the feed steam (stream 26) for the IP turbine.

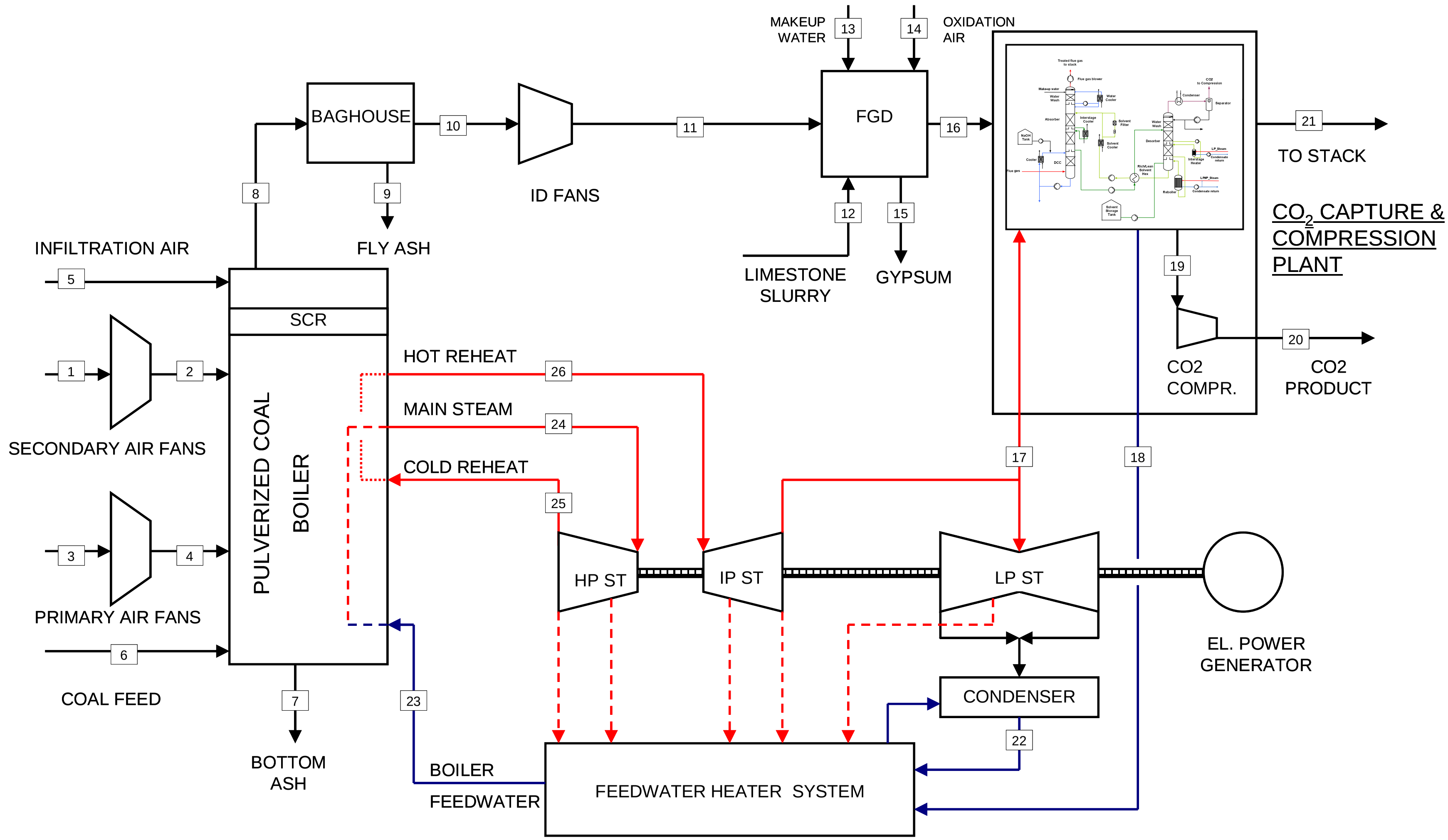


Exhibit 4-1 Block Flow Diagram of Subcritical PC power plant with CO_2 Capture and Compression

4.2. Key System Assumptions

Exhibit 4-2 summarizes the key system assumptions used in this study, which are identical to those used in the DOE/NETL-2007 report [Ref. 1].

Exhibit 4-2. Subcritical PC Plant Study Configuration Matrix

Steam Cycle, MPa/^{o}C/ ^{o}C (psig/ ^{o}F/ ^{o}F)	16.5/566/566 (2400/1050/1050)
Condenser Pressure, mm Hg (in Hg)	50.8 (2)
Boiler Efficiency, %	89
Cooling water to condenser, ^{o}C (^{o}F)	16 (60)
Cooling water from condenser, ^{o}C (^{o}F)	27 (80)
Stack temperature, ^{o}C (^{o}F)	32 (89)
SO_2 Control	Wet Limestone with Forced Oxidation
FGD Efficiency, %	98
NOx Control	LNB w/OFA and SCR
SCR Efficiency, %	86
Ammonia Slip (end of catalyst life), ppmv	2
Particulate Control	Fabric Filter
Fabric Filter efficiency, %	99.8
Ash distribution, Fly/Bottom	80% / 20%
Mercury Control	Co-benefit Capture
Mercury removal efficiency, %	90
CO_2 Control	BASF OASE® Blue Technology
CO_2 Capture, %	90
CO_2 Sequestration	Off-site Saline Formation

4.3. Process Integration Options

As the DOE/NETL-2007 study [Ref. 1] demonstrates, 90% CO_2 capture from a 550 MWe subcritical PC power plant increases the energy (coal) demand by approximately 47% above a 550 MWe power plant without CO_2 capture. BASF's OASE® blue technology amine-based solvent in combination with the innovative Linde-BASF PCC plant design leads to reduced energy penalties of integrated PC power plant with PCC of more than 30% relative to the reference MEA-based process. Further reductions of more than 10% of incremental energy for PCC can be achieved by exploring and optimizing various process integration options.

Most of the existing PC power plants do not have steam turbine cycles specifically designed and optimized for PCC units. This is consistent with the DOE/NETL-2007 study [Ref. 1], where steam for PCC plant (Cases 10 and 12) is extracted from a IP-LP crossover pipe at 1.16 MPa (167 psia) and 395^{o}C (743^{o}F).

The Linde-BASF PCC plant design requires LP steam (about 5 Bara) for solvent regeneration. When IP-LP steam is available at significantly higher pressures (such as required for this study, i.e. identical to Case 9 and Case 10 of [Ref. 1]), a very efficient integration option is to utilize a Back Pressure Steam Turbine (BPST) to expand steam from greater than 10 Bara to less than 6 Bara, which can generate a significant amount of electrical power and reduce power withdrawal from the PC power plant for and the PCC and CO_2 compression units. Linde has a pending patent application with the U.S. Patent and Trade Office for this configuration [Ref. 5]. The quantification of energy reduction with this approach is presented in Sections 5.2 and 5.3

Another integration option is to partially recover sensible heat from the flue gas stream before it enters the FGD unit, and to use it for generating a significant amount of LP steam ($P < 4$ Bara). This can be effectively used to reduce boiler steam requirements for solvent regeneration by utilizing a stripper interstage heater, as mentioned in Section 3.2. This heat recovery option is similar to the extraction of heat in an economizer. An additional benefit of the proposed waste heat recovery from flue gas is a significant reduction in FGD water usage. Linde has a pending patent application with the U.S. Patent and Trade Office for this configuration [Ref. 4]. Exhibit 4-3 outlines the above two integration options from the overall PCC - power plant perspective, while Exhibit 4-4 provides some more details of the correspondingly modified PCC plant. Sections 5.2 and 5.3 provide quantification of the resulting benefits and address the limits for techno-economically-viable waste heat recovery.

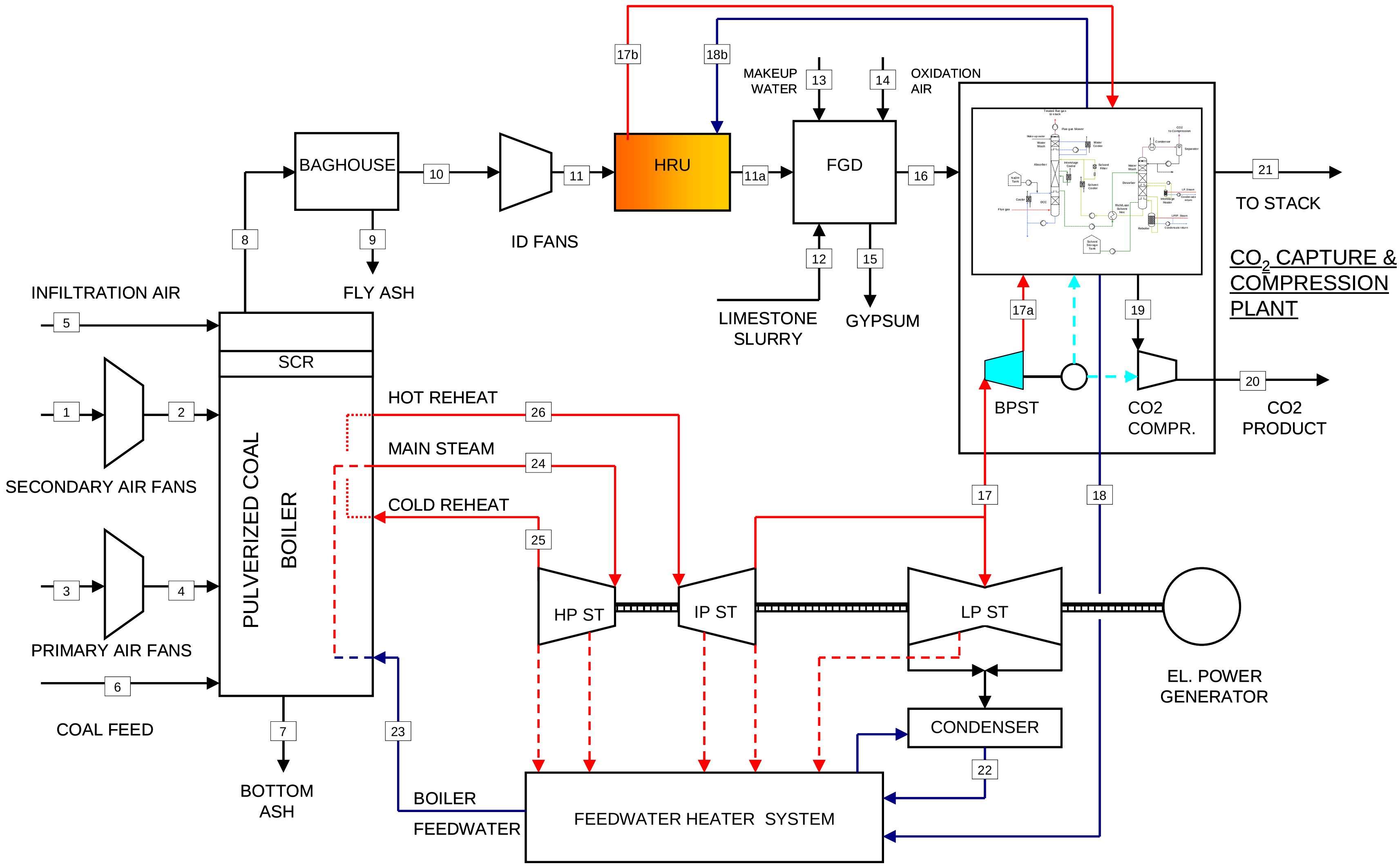


Exhibit 4-3 Block Flow Diagram of Integrated PC power plant with CO_2 Capture and Compression

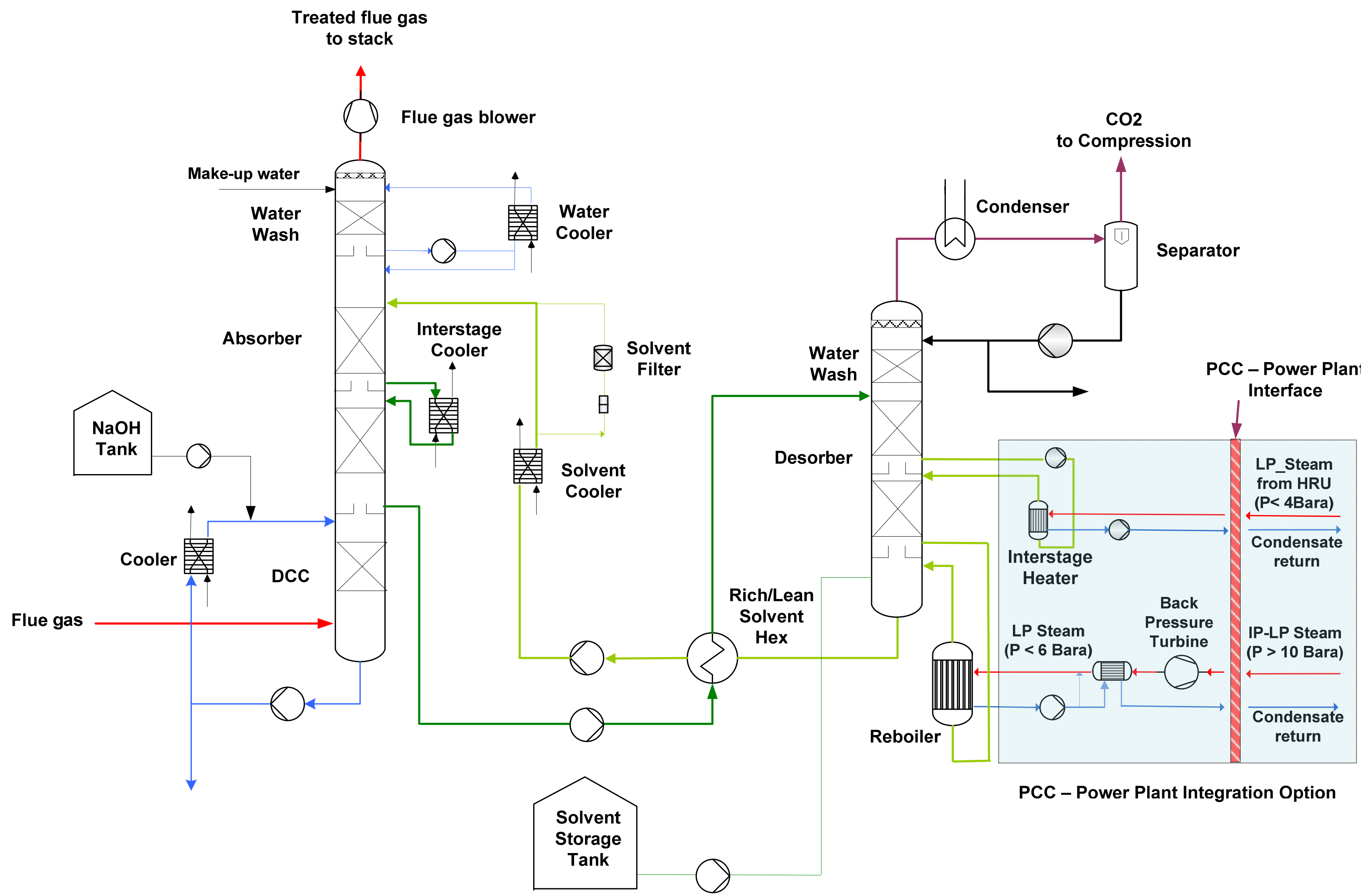


Exhibit 4-4 Linde-BASF PCC Plant integrated with PC Power Plant

5. Techno-Economic Evaluations

5.1. Modeling Approach and Validation

Detailed techno-economic evaluations have been accomplished by utilizing UniSim software as a generalized computational platform for rigorous calculations of physical and thermodynamic properties of water, steam, and multi-component mixtures, along with related material and energy balances around each individual unit operation of the integrated power plant with CO_2 capture system. BR&E ProMax® software has been used for parametric studies of key PCC process parameters, while BASF's proprietary package has been used for final, accurate predictions of mass and heat transfer rates, as well as for the kinetics of complex chemisorption reactions between CO_2 and solvent components. Resulting performance parameters of the optimized PCC plant have been fully-integrated with the UniSim simulation of the entire power plant system with CO_2 capture.

The first step in validating the modeling approach was to reproduce material streams and related energy balances around the PC boiler reported Cases 9 and 10 of the DOE/NETL-2007 study [Ref. 1]. It has been confirmed that the UniSim program with incorporated Illinois No. 6 coal properties and feed rates successfully predicts the flow, pressure, and temperature values for high-pressure steam and reheated IP steam based on specified values of boiler feedwater and cold reheat streams, along with exactly the same composition and temperature of the flue gas, including bottom ash and fly ash content. The next step has been to incorporate the specified performance of the wet FGD in order to accurately predict the flow, pressure, temperature, and composition of the feed stream to the PCC plant.

The most important step in verifying and calibrating the simulation model has been to tune the performance parameters of all steam turbine stages used in Cases 9 and 10 of DOE/NETL-2007 report in order to reproduce the reported pressure, temperature, and flowrate values of all steam and water streams within the steam-water cycle reported in the 2007 study. This enabled consistent performance comparisons when the Linde-BASF PCC technology is integrated with the power plant.

Exhibit A-1 in Appendix A provides the details of our overall simulation of Case 10 referenced in 2007 study [Ref. 1], while Exhibit A-2 provides all calculated pressure, temperature, and flowrate values within the steam-water cycle of Case 10, along with total produced power, net produced power, and net process efficiency.

5.2. Performance Results

A series of simulations were performed with various operating parameters of the PCC plant incorporating the Linde-BASF technology and with different levels of process integration with the PC power plant.

Two sets of performance results are presented in more detail, for the following two process configuration options:

- LB-1 Option: Subcritical PC power plant integrated with Linde-BASF PCC plant.
- LB-2 Option: Subcritical PC power plant integrated with Linde-BASF PCC plant utilizing waste heat recovery and power cogeneration for internal heat and power requirements.

The Linde-BASF PCC plant is designed in both cases to minimize energy requirements for CO_2 recovery and compression. As commented in Section 3, in addition to using advanced, high-performance BASF OASE® blue solvent, it also incorporates several novel process options and design features, including: novel absorber with advanced high-performance packing, integrated DCC and wash units, interstage gravity-driven cooler, and flue gas blower downstream of absorber. While the absorber operates at slightly sub-atmospheric pressure, solvent regeneration is performed in the stripper operating at 3.4 bara at the top of the column, which significantly reduces power requirements for CO_2 compression. This has been chosen to be the upper limit considering the increasing solvent degradation expected at higher stripper temperatures, which correspond to higher stripper pressures. In addition, the water balance and energy consumption have been optimized by cooling the flue gas and lean amine solvent entering the absorber to 25°C, while maintaining the condenser temperature at 20°C. The solvent circulation rate is also optimized for the above process conditions to minimize the heat requirement for solvent regeneration.

Exhibit 5-1 summarizes resulting energy requirement elements for CO_2 capture and compression for the two Linde-BASF process options, while Exhibit 5-2 illustrates corresponding energy savings with respect to DOE/NETL-2007 Case 10 [Ref. 1].

Exhibit 5-1 Specific energy demand for 90% CO_2 capture and compression to 15.3 MPa

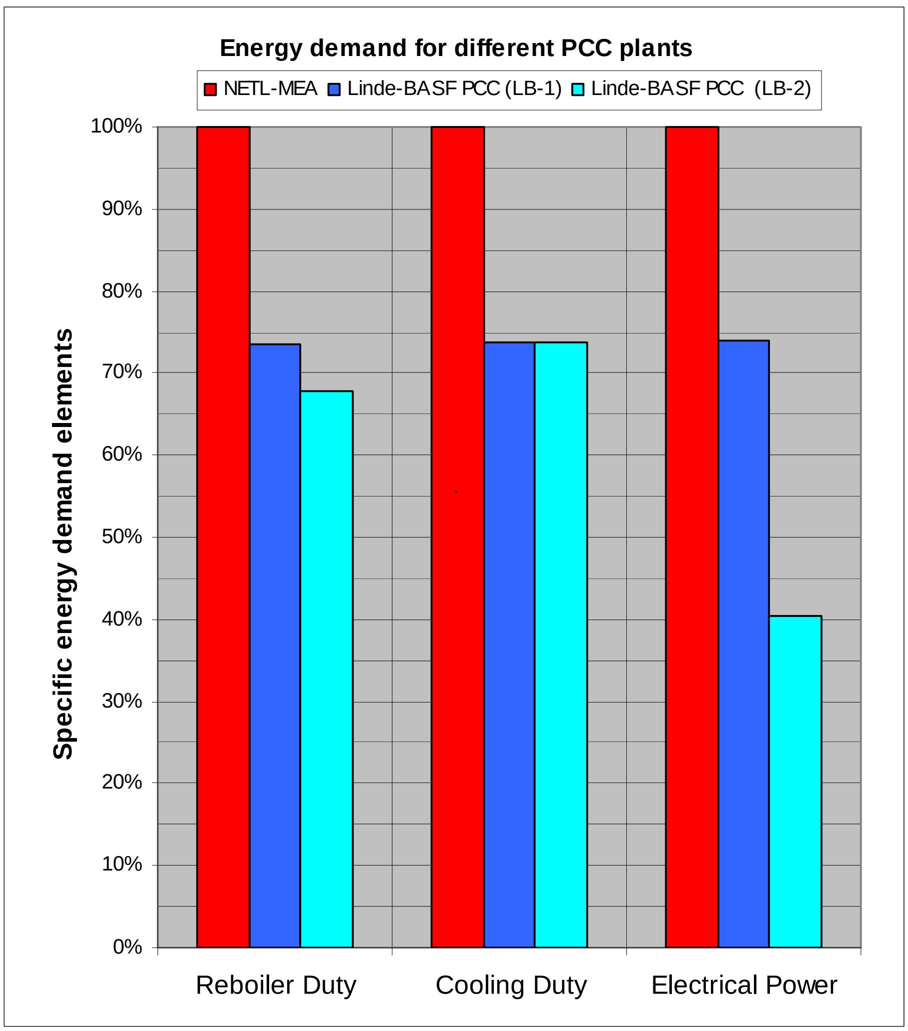
Utility	NETL-MEA	LB-1	LB-2
Reboiler Duty, (GJ/MT_CO_2)	3.55	2.61	2.41*
Cooling Duty, (MW_{th}hr)/(MT_CO_2)	1.64	1.21	1.21
Electrical Power (kW_ehr/MT_CO_2)	119.9	88.7	48.5**

* 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

Exhibit 5-2 Specific energy demand per unit of captured and compressed CO_2



The BASF OASE® blue solvent itself contributes with 21.7% to the incremental reduction of reboiler duty relative to the NETL-MEA reference case, while PCC process design and optimization reduces reboiler duty for additional 4.8% (LB-1 case). Finally, the heat integration further reduces reboiler duty for additional 5.6% (LB-2 case).

It is important to realize that the above savings for CO_2 capture and compression in terms of heating, cooling, and power requirements translate to a significant reduction in total energy required for the integrated power plant with PCC plant, leading to further reduced size of the power plant.

Exhibit 5-3 illustrates the net reduction of incremental coal requirement for a power plant with CO_2 capture (utilizing Linde-BASF instead of MEA PCC) versus a power plant without CO_2 capture.

Exhibit 5-3 Effect of Linde-BASF technology on energy reduction for CO_2 capture and compression

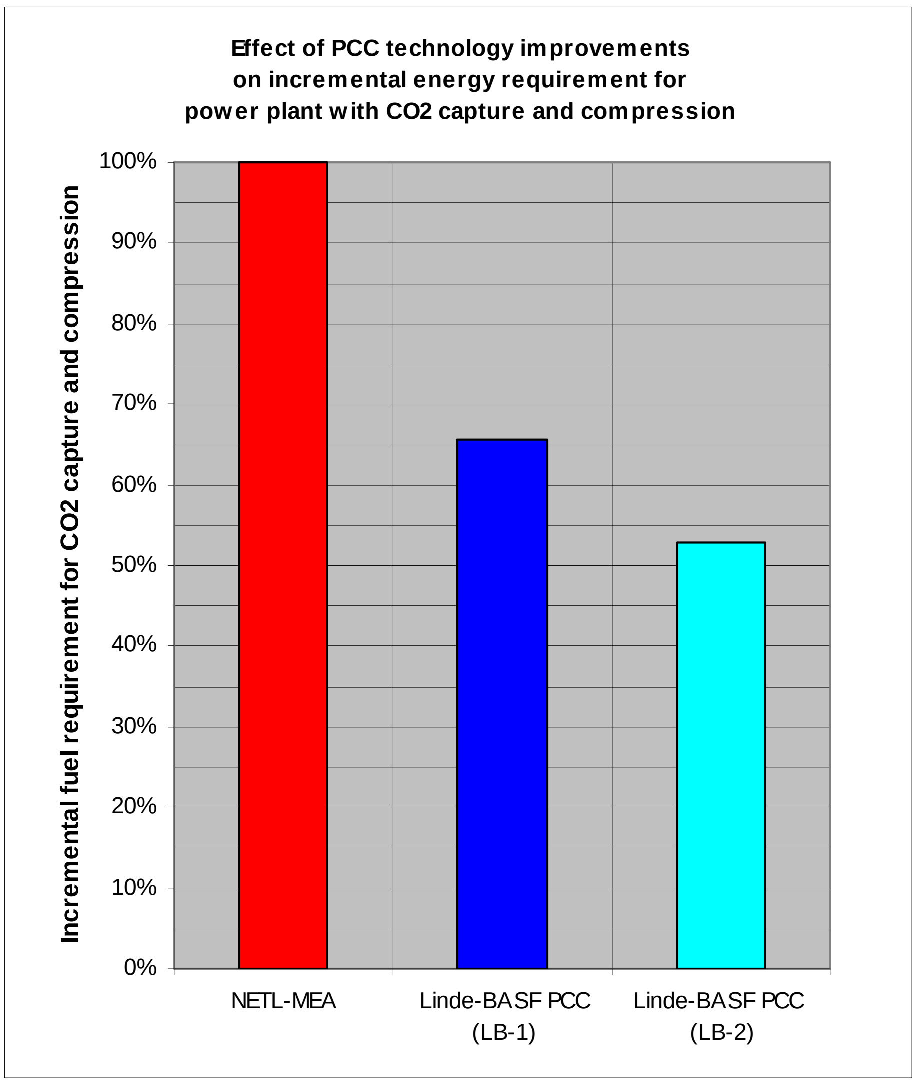


Exhibit 5-4. Net power plant efficiency improvements

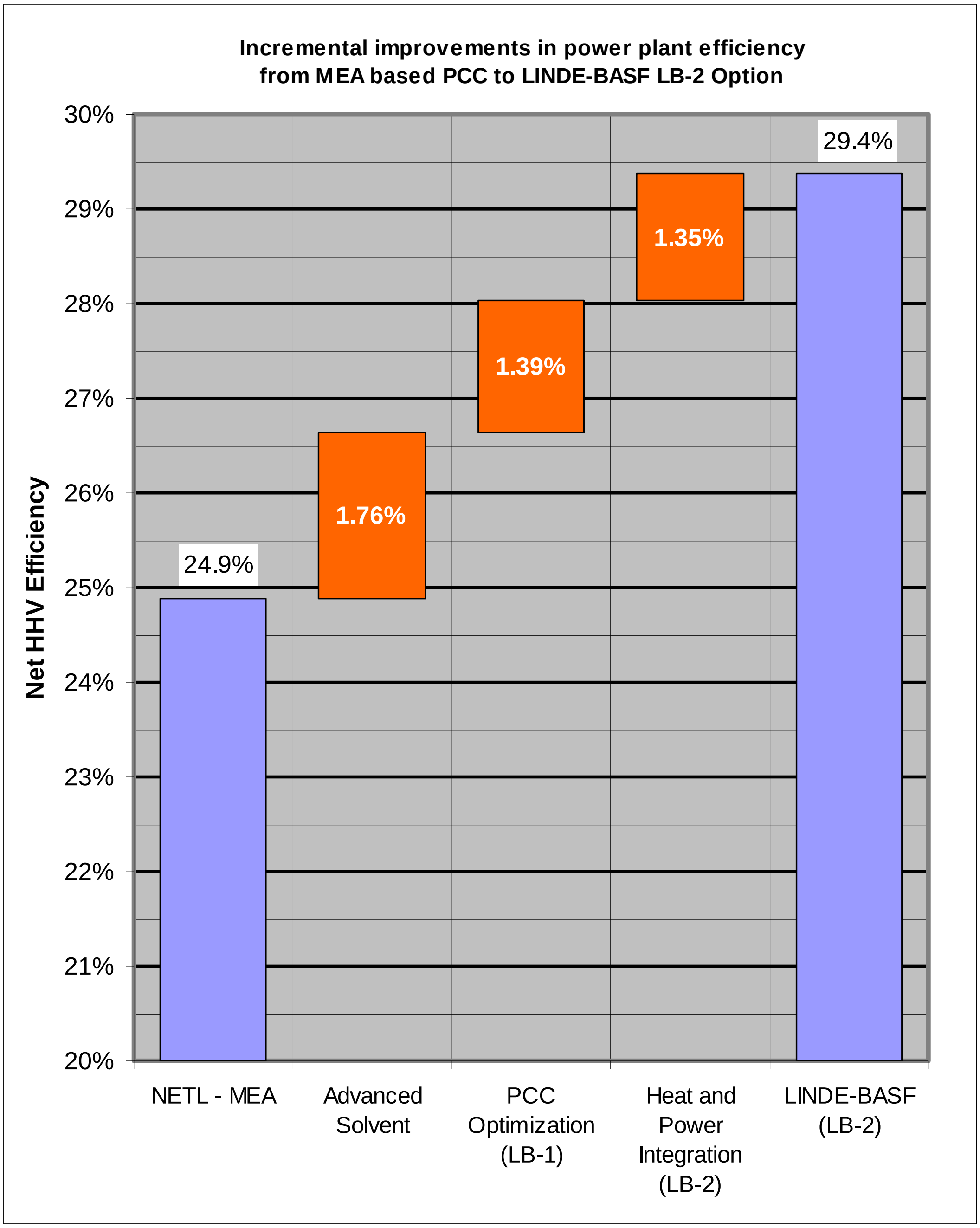


Exhibit 5-4 illustrates that the advanced BASF OASE® blue solvent contributes the most to the overall plant efficiency increase. The optimization of PCC plant, the second largest improvement step, includes significantly reduced CO_2 compression due to solvent regeneration at higher pressure (3.4 bara) and condensation at low temperature (20°C), as well as optimized heat management and reduced energy for the flue gas blower and solvent circulation pumps. The heat and power integration options (outlined in Exhibit 4-3) also increase the net plant efficiency. The IP-LP steam requirement for the reboiler is significantly reduced by recovering the sensible waste heat from the flue gas and transferring it, via generated low-pressure (< 4 bara) steam, to the stripper by utilizing an interstage heater, as commented in Section 4.3. Substantial power reduction for PCC and CO_2 compression requirements is achieved by optimized management of IP-LP steam extracted from the main power plant by utilizing a BPST before using LP steam for the reboiler duty.

Exhibit 5-5 provides overall material and energy balances for a PC power plant integrated with Linde-BASF PCC technology for Case LB-1, while Exhibit 5-6 provides detailed material and energy balances for the water-steam cycle of the corresponding power plant, along with total power production and net power plant efficiency values.

Exhibits 5-7 and 5-8 provide the same set of information for Option LB-2, which explores heat and power integration (shown in Exhibit 4-3). In this process option, as much as 32.8 MWth of waste heat from the flue gas is recovered by cooling it down from 375^{o}F (stream 11 Exhibits 4-3 and 5-7) to 302^{o}F (stream 11a), while producing 121,552 lb/hr of steam (at 52.4 psia and 284°F – stream 17b). This steam is used in the interstage heater, which effectively reduced IP-LP steam extraction from the steam turbines by ~8% and consequently reduced specific reboiler duty requirement from 2.61 to 2.40 MJ/kg CO_2. In general, this concept of re-utilization of recovered waste heat could be extended to significantly lower temperature than our imposed condition of 150°C, which is governed by the criteria to avoid acid condensation on the surface of the heat exchanger, which would cause significantly more expensive materials of construction and consequently diminished benefits for the resulting cost of electricity.

Optimized IP-LP steam management has led to additional energy reduction for PCC. As shown in Exhibit 4-3, extracted IP-LP steam (stream 17 at 167.7 psia) was expanded (stream 17a) to the required pressure (79.8 psia) for the reboiler by utilizing a BPST, which generated as much as 25.6 MWe and significantly reduced the power requirement for the PCC plant (see Exhibits 5-2 and 5-3). Condensate (stream 18) is returned to the feedwater heater system at identical conditions as in reference Case 10 [Ref. 1].

Comparison of overall plant performances for DOE/NETL Case 10, Linde-BASF Option LB-1 and Linde-BASF Option LB-2 are summarized in Exhibit 5-9. Environmental indicators for the same three PCC options are summarized in Exhibit 5-10.

Stream Properties	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)	149,243	149,243	45,846	45,846	3,450	0	0	209,992	0	209,992	209,992	7,286	35,833	2,527	20,673
V-L Flowrate (lb/hr)	4,306,488	4,306,488	1,322,908	1,322,908	99,553	0	0	7,054,581	0	6,246,231	6,246,231	131,265	645,542	72,906	372,431
Solid Flowrate (lb/hr)	0	0	0	0	0	572,810	11,113	44,450	44,450	0	0	57,388	0	0	92,790
Temperature (F)	59	67	59	77	59	59	350	350	350	350	368	59	59	59	135
Pressure (psia)	14.7	15.3	14.7	16.1	14.5	14.7	14.4	14.4	14.4	14.2	15.3	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	-1,065.4	-6,820	-6,819.7	-41.9	-6,770.7
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	61.34
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

Stream Properties	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26
V-L mol. fract.	1	1	0	1	1	1	0	0	1	1	1
Ar	0.0079	0.0000	0.0000	0.0000	0.0000	0.0106	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.1319	0.0000	0.0000	0.9925	0.9998	0.0177	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	0.1717	1.0000	1.0000	0.0073	0.0000	0.0464	1.0000	1.0000	1.0000	1.0000	1.0000
N2	0.6650	0.0000	0.0000	0.0001	0.0001	0.8937	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0234	0.0000	0.0000	0.0000	0.0000	0.0315	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
HCl	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
V-L Flowrate (lbmol/hr)	234,171	72,106	72,106	68,114	27,799	174,247	154,772	269,160	269,160	247,973	247,973
VL Flowrate (lb/hr)	6,696,460	1,299,000	1,299,000	1,227,089	1,223,372	4,893,969	2,788,230	4,848,953	4,848,953	4,467,262	4,467,262
Solid Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0
Temperature (F)	135	743	368	68	89	89	102	484	1,050	690	1,050
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
Enthalpy (Btu/lb)	-1,390.8	-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
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
Molecular Weight	28.60	18.02	18.02	18.02	44.01	28.09	18.02	18.02	18.02	18.02	18.02

Stream Number

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

Exhibit 5-5 M&E Balances for LB-1 Option (in reference to Exhibit 4-1)

Stream Number

Stream Properties	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Flow (lb/hr)	4,862,203	4,862,203	4,478,862	4,478,862	2,592,008	195,836	1,302,400	2,141,683	195,836	2,795,900	2,795,900	2,795,900	2,795,900	2,795,900	2,795,900
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)	2,795,900	4,862,203	4,862,203	4,862,203	4,482,218	342,789	223,790	197,324	72,430	169,289	94,475	117,659	8,056	3,529	2,480
Temperature (F)	284.7	363.2	370.8	424.2	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)	2,047	342,789	566,579	72,430	241,720	336,195	453,853	456,326	1,302,400	25,350
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	-6,765	-6,506	-5,381

Total ST Electrical Power:	646.7	MW
Net Electrical Power:	550.0	MW
Net Efficiency:	28.0	%

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

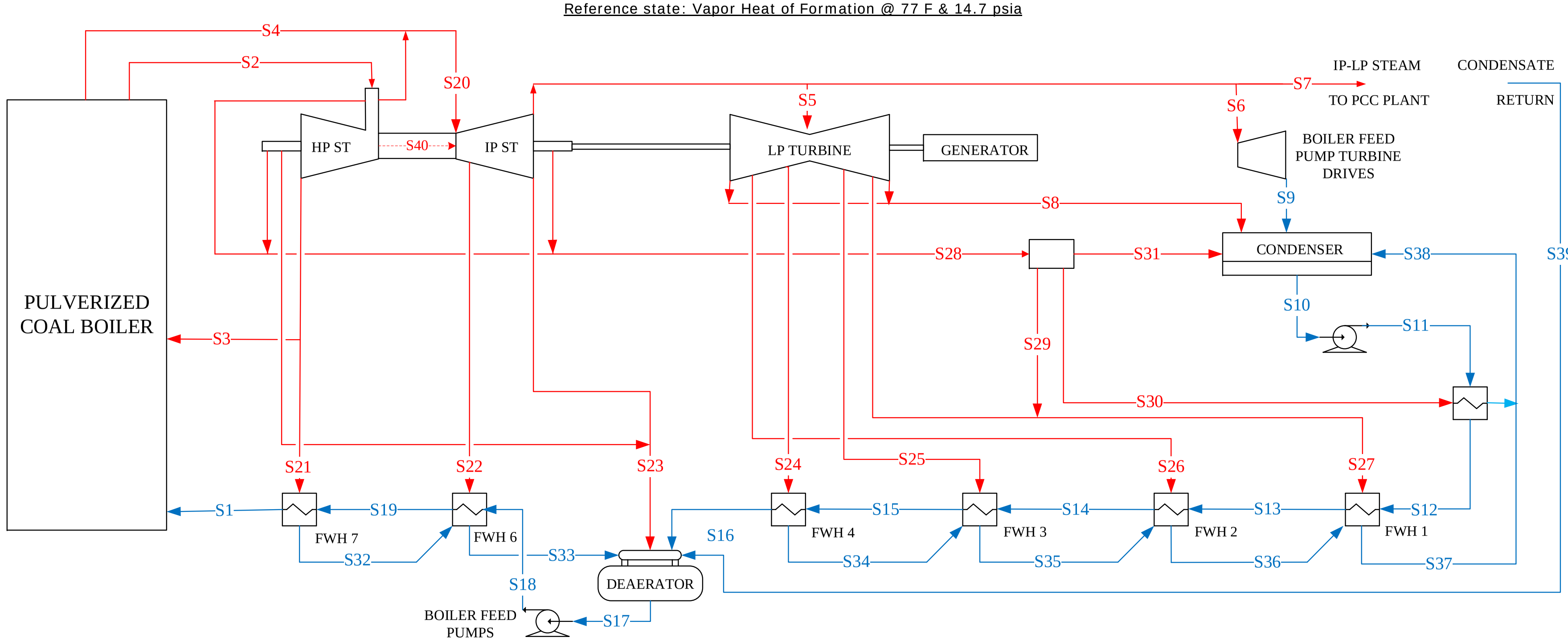


Exhibit 5-6 Heat and Mass Balance: Power plant with Linde-BASF PCC Technology - Case LB-1

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

Exhibit 5-7 M&E Balances for LB-2 Option (in reference to Exhibit 4-3)

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

Stream Properties	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

Stream Properties	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

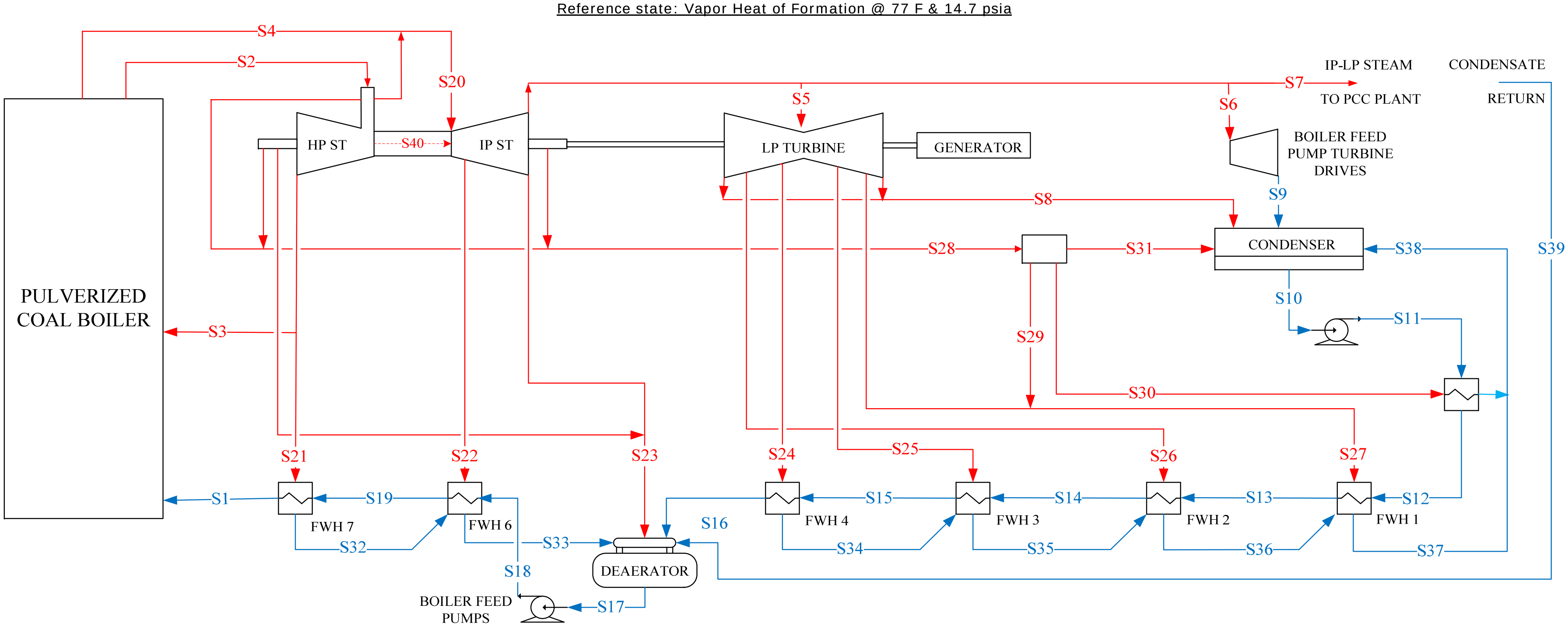


Exhibit 5-8 Heat and Mass Balances: Power plant with Linde-BASF PCC Technology - Case LB-2

Exhibit 5-9 Influence of PCC technology options on PC power plant performance

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)

As shown above, the total auxiliary power requirements for both options of Linde-BASF technology are significantly lower than for MEA-based PCC technology. In addition, the utilization of heat and power integration in option LB-2 further reduces coal consumption and consequently leads to the highest net plant efficiency of 29.4%

Exhibit 5-10 Environmental benefits of LINDE-BASF PCC Technology

	Annual Air Emissions (85% capacity factor)		
	NETL_2007 Case 10	LINDE-BASF LB-1	LINDE-BASF LB-2
CO2 (MT/Year)	517,000	459,372	438,219
NOx (MT/Year)	1,783	1,584	1,511
PM (MT/Year)	331	294	281
Hg (kg/Year)	29	26	25
	Hourly Water Consumption		
Raw Water Makeup (MT/hr)	46.1	35.8	34.2

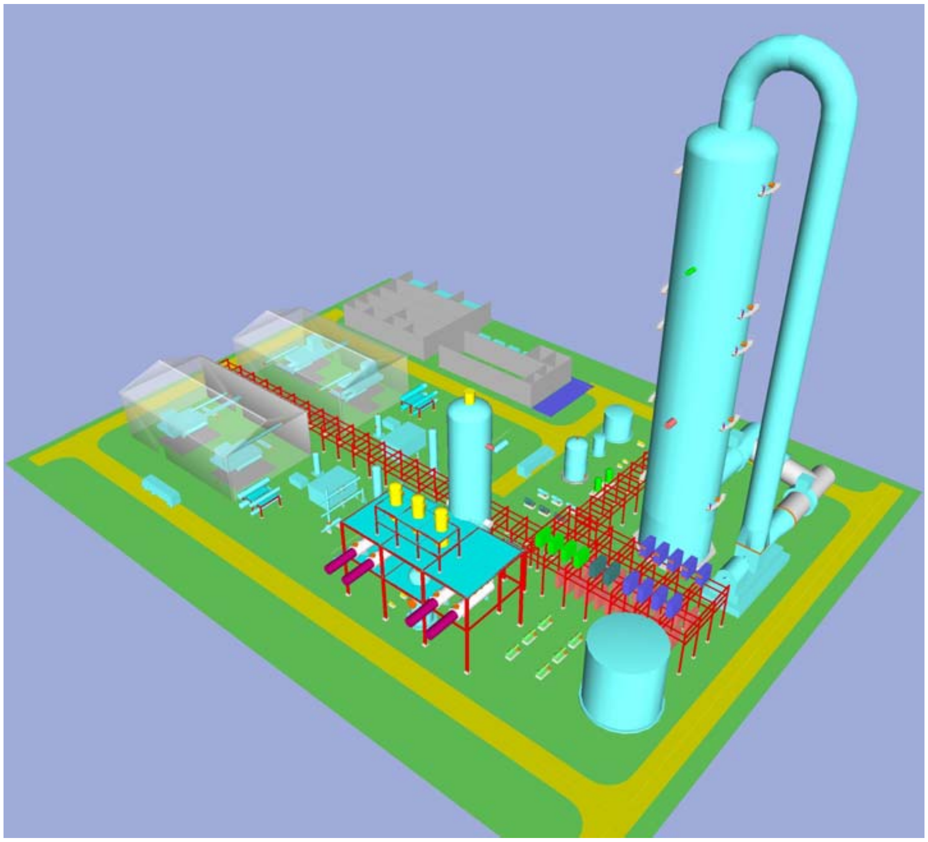
The set of presented data confirms a superior performance of Linde-BASF PCC technology compared with the MEA-based PCC option. The environmental benefits presented are consistent with demonstrated improvements in performance indicators, with reductions in all key indicators across the board (CO_2, NOx, Hg and PM emissions reduced for 11.1% and 15.2% for the LB-1 and LB-2 options respectively, compared to MEA-based option), and with reduced fresh water makeup requirements of 22.4% (LB-1) and 25.7% (LB-2).

5.3. Capital Cost Estimates

PCC Plant Design

The Linde-BASF PCC plant for this study is an optimized version of previously reported Linde-BASF PCC plant options for different European studies, where absorbers up to 18 m in diameter were anticipated [Ref. 3]. As documented in Section 5.2, the Linde-BASF PCC technology reduces the coal feed rate and consequently the total flow rate of the flue gas entering the PCC plant by 11.1% (option LB-1) and 15.2% (option LB-2), relative to the reference Case 10 of NETL_2007 study. With 90% CO_2 capture, it translates to 13,359 TPD (option LB-1) or 12,744 TPD (option-2) CO_2 captured from a 550 MWe PC power plant, which makes it feasible to employ a single absorber with a single regenerator PCC plant design by utilizing high-performance structured packing and optimized hydraulic design, as illustrated in a 3D schematic below. The resulting plot area for the Linde-BASF PCC plant is approximately 180 m x 120 m. A two-train PCC design similar to NETL reference Case 10 would require a 40 to 50% larger area.

Exhibit 5-11 3D Image of Linde-BASF PCC Plant Design for 550 MW PC Power Plant



PCC Plant Cost

The total plant cost (TPC) for the novel Linde-BASF PCC technology was estimated based on Linde's proprietary methodology of estimating the cost for new, commercial process plants, which included as many actual recent vendor quotes as available based on recent commercial proposals and studies. The accuracy of the final PCC plant cost was estimated to be within +/- 30% in this study. As per DOE/NETL requirements, the resulting TPC also includes 20% process contingency, as well as 4% project contingency, as shown in Exhibit 5-12. In case of LB-2 option, additional cost for heat and power integration system is presented, as well.

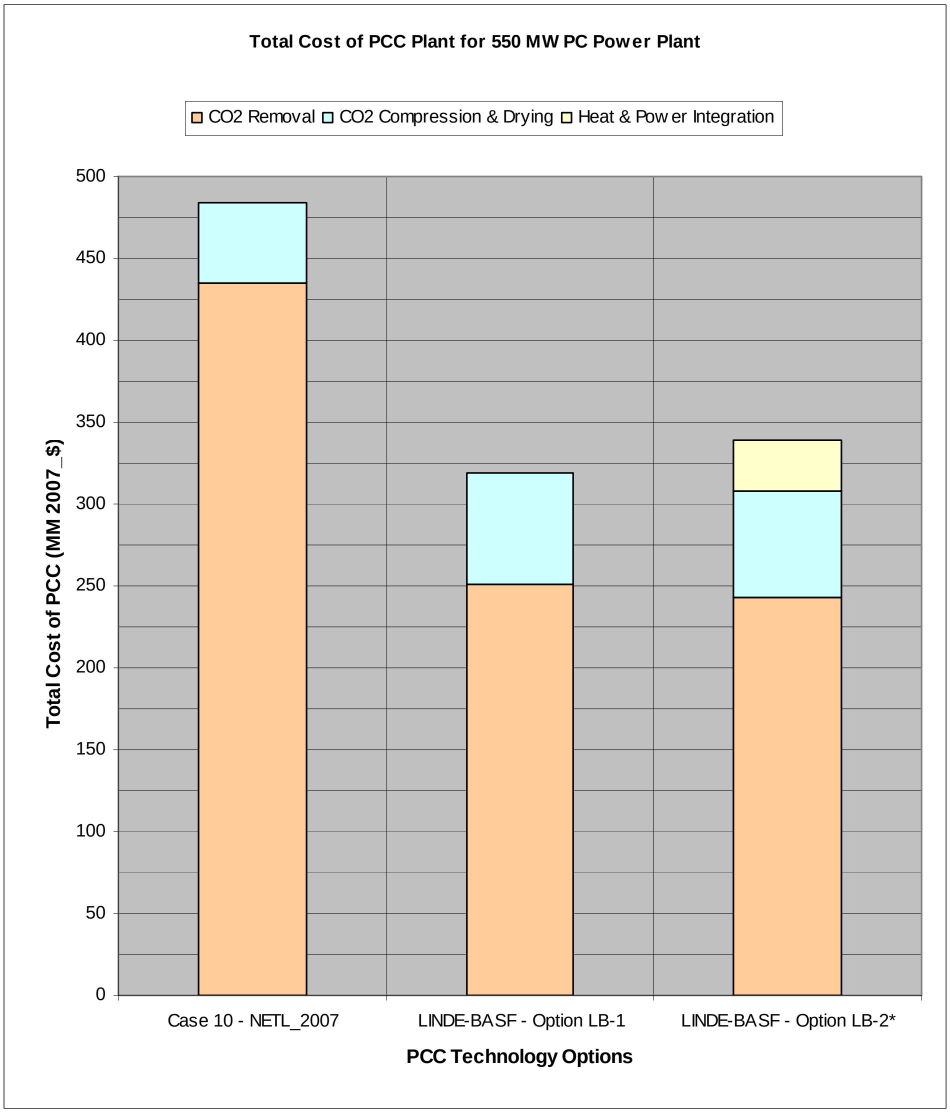
Exhibit 5-12. Linde-BASF PCC plant cost details

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**

The reduced plant cost for both Linde-BASF PCC plant options for the capture and compression of CO_2 from a 550 MW PC power plant is a result of the combined effects of an advanced PCC plant design (utilizing a single train CO_2 recovery plant with advanced design solutions and construction materials), and of the reduced capacity of the PCC plant due to the increased overall efficiency of the PC power plant integrated with Linde-BASF PCC technology.

Exhibit 5-13 shows the resulting reduction of TPC and its elements for the two Linde-BASF PCC options (LB-1 and LB-2) with respect to reference Case 10, which utilizes a MEA-based solvent. While the total plant cost for the Linde-BASF CO_2 removal system is significantly lower than for the reference Case 10 of NETL_2007 study [Ref. 1] due to the multiple effects explained above, our estimate for the CO_2 compression and drying system is measurably higher than for the reference Case 10.

Exhibit 5-13 Comparison of Total PCC Plant Costs



550 MW PC Power Plant			
	NETL_2007 Case 10	LINDE-BASF LB-1	LINDE-BASF LB-2*
CO2 Captured (TPD)	15,049	13,359	12,744
CO2 Removal system (MM $)	435.4	251	273.6
CO2 Compression & Drying (MM$)	49.1	65.8	63.7
PCC Plant Cost (MM 2007_$)	**484.5**	**316.9**	**337.2**
Cost Reduction wrt Case 10 (%)	**0.0%**	**34.6%**	**30.4%**

* For LB-2 option, the cost for heat and power integration is included in CO2 Removal system

We strongly believe that the DOE/NETL_2007 estimate for the cost of the CO_2 Compression and Drying system of 49.059 MM $ presented for Case 10 is too low, particularly when it is taken into account that the CO_2 flow rate in the reference Case 10 is 12.6% and 18.1% higher than in the options LB-1 and LB-2 estimated from the latest quotes from multiple vendors as 65.8 MM$ and 63.7 MM$, respectively. Additional significant incremental increase for the TPC for the CO_2 compression system for the reference NETL Case 10 (relative to Linde-BASF estimates for the CO_2 compression cost) should arise from the fact that the pressure of the CO_2 recovered stream from the regenerator is at 1.6 Bara (23.5 psia) in NETL Case 10, while in the options LB-1 and LB-2 of the Linde-BASF PCC technology, the feed to the compression section is at 3.3 Bara (47.9 psia), which, in turn, significantly reduces the total power rating of the CO_2 compression system and completely eliminates the first (largest) compression stage out of six stages used in the NETL_2007 study.

Total Plant Cost Estimates

In addition to estimating the total cost for Linde-BASF PCC plant options LB-1 and LB-2 with the methodology outlined above, it is also necessary to estimate the cost of the PC power plant in order to obtain the TPC value necessary for calculation of the LCOE (detailed in Section 2).

For this study, after consulting different sources of information, a frequently practiced approach to use estimated exponential scaling factors to calculate the cost of a plant with different capacity than the original plant with known cost was adopted. This approach was verified not only from reported TPC values from the NETL-2007 study for power plants with and without CO_2 capture, but also after completing a due diligence from the communications and actual cost information obtained from Santee Cooper for their commercial subcritical and supercritical power plants, similar in size as in this study. Most of the plant cost elements and proportions between different items remained very similar to those reported in the NETL study when compared on an equivalent basis, with the only significant exception being the site-specific cost that included foundations, buildings, miscellaneous civil expenses, etc. However, since the evaluation basis for this techno-economic analysis are strictly defined and are identical as in the NETL-2007 Case 9 and Case 10 examples [Ref. 1], the above mentioned difference for site-specific cost is not relevant for this study.

After carefully examining interdependences of reported cost elements by all equipment elements and resulting accounts from the NETL_2007 study (Case 9 without PCC capture versus Case 10 with PCC capture) and from obtained information from Santee Cooper, it was concluded that as the first approximation, the TPC of the entire power plant (except independently estimated TPC for the PCC plant) can be scaled-down as a function of the coal feed rates used in different process options (denoted as SP-S, Single Parameter Scaling methodology).

From the TPC elements for the Cases 9 and 10 [Ref. 1], a single exponential scaling factor of 0.669 was derived and used to estimate the TPC for a power plant integrated with Linde-BASF PCC technology, except for the PCC plant itself, for which, the TPC values for the two selected options (LB-1 and LB-2) were independently estimated (Total PCC Plant Cost shown is in Exhibit 5-12).

Another approach explored in this study of estimating the TPC of the entire power plant was to scale-down the TPC for most of the categories with the total coal consumption, by utilizing multiple, individually determined scaling factors for each of those categories (from reported cost elements from the Case 9 and Case 10 of NETL 2007 study and information received from Santee Cooper), with two notable exceptions: (1) the cooling water system was scaled with calculated total cooling duty for the entire plant; and (2) the cost of steam turbine generators was scaled with the total power production. As expected, some of the plant units have a very weak dependence on the capacity (such as improvements to site, buildings, structures, etc.), which was accounted by back-calculated (from cost for Case 9 and Case 10 plants) very low values of scaling factors (for example, calculated 0.065 scaling factor for buildings and structures). This methodology is referred to as MP-S (Multiple Parameter Scaling).

Exhibit 5-14 shows the total plant capital cost elements by cost accounts and illustrates that the difference between TPC values calculated while utilizing SP-S or MP-S cost scaling methodologies are less than 1%

While it is understood that neither of the two approaches is perfect, it is believed that for this study they facilitate consistent predictions of the incremental change in the capital cost of the integrated PC power plant with PCC when Linde-BASF technology is utilized instead of MEA-based technology used by NETL in 2007 study.

In Section 5.4, the TPC values for LB-1 and LB-2 options were derived by scaling-down the cost of the entire power plant (except the PCC plant) with a single exponent scaling factor of 0.669

(as explained above), while Section 5.5 quantifies the influence of different methodologies used for the TPC estimates, and different options for the CO_2 transport, storage, and monitoring (TSM) calculations, on the resulting LCOE values.

Exhibit 5-14 Itemized Total Plant Capital 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**

5.4. Levelized Cost of Electricity

The LCOE for a PC power plant with CO_2 capture and compression utilizing the Linde-BASF PCC technology has been calculated using the equation shown in Section 2, along with stated values of economic parameters that are identical to the methodology used in NETL_2007 study, as well as with unchanged unit cost elements of consumables used in the Exhibit 4.10 of DOE/NETL 2007/1281 report. The only exception was a unit cost for the BASF OASE® blue solvent, which has been estimated to be three times the unit price of the MEA solvent used in the NETL_2007 study. In order to consistently compare the effects of new PCC technology on incremental LCOE values relative to NETL_2007 study, all costs are expressed in 2007_$, similarly as NETL_2010 study also used 2007_$.

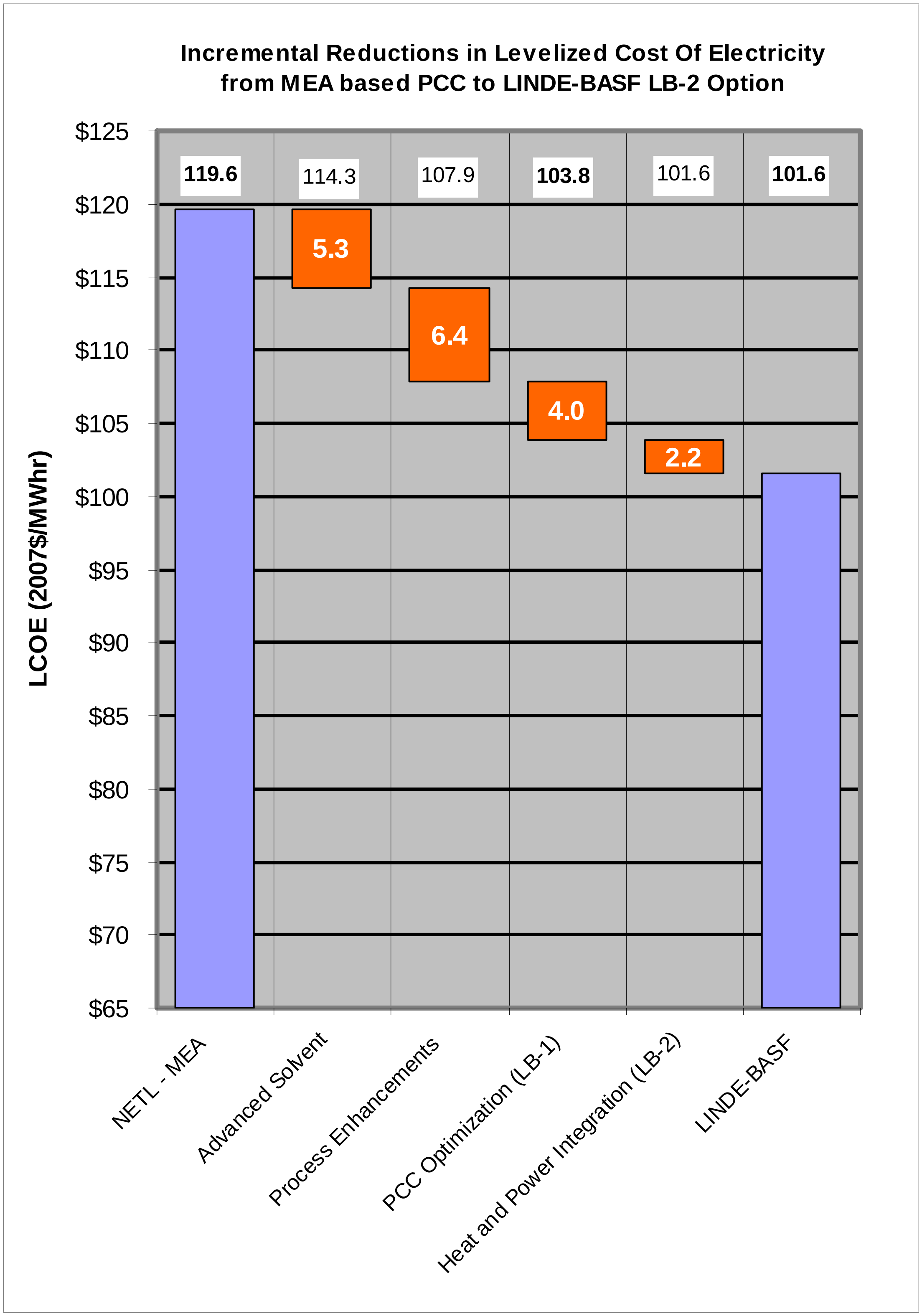
Exhibit 5-15 summarizes the major annual operating and maintenance cost elements for the reference Case 10 utilizing MEA-based PCC technology, and for the two selected Linde-BASF PCC options.

Exhibit 5-15 Summary of Annual Operating and Maintenance Expenses

Annual O&M EXPENSES for 550 MW PC Power Plant with PCC (2007$)			
	NETL_2007 Case 10	LINDE-BASF LB-1	LINDE-BASF LB-2
TOTAL FIXED OPERATING COST	**20,541,525**	**20,541,525**	**20,541,525**
Maintenance Material Cost	15,442,820	12,971,601	12,861,284
Water	3,243,688	2,517,837	2,409,044
Chemicals	14,976,086	15,202,543	14,502,509
SCR Catalyst	1,168,014	1,030,996	983,521
Ash Disposal	3,454,212	3,070,783	2,929,382
TOTAL VARIABLE OPERATING COST	**38,284,820**	**34,793,760**	**33,685,740**
TOTAL FUEL (Coal @ 42.11 $/ton)	**101,365,989**	**90,069,209**	**85,921,776**

Exhibit 5-16 shows incremental step reductions in LCOE values while changing PCC options from an MEA-based technology (NETL-Case 10) toward Linde-BASF PCC technology without or with heat and power integration options (LB-1 and LB-2, respectively).

Exhibit 5-16: Incremental LCOE reduction steps (SP-S methodology for TPC)



The following set of assumptions was used for this exhibit:

- The TPC values for the entire power plant (except for the PCC plant) were estimated by scaling-down the cost from the Case 10 (NETL_2007 study) with the rate of coal combustion and derived value of a single exponential scaling factor of 0.669.
- The PCC plant cost, estimated from the latest vendors quotes received in 2011 and 2012, was expressed in 2007_$ by using a cumulative cost escalation factor of 9.2% (Source CEP Index January 2007 to January 2012).
- The CO_2 TSM was calculated by using 4.05 \$/ton_CO_2, as required by the DOE for this award.

The graph above clearly demonstrates the critical steps in LCOE reduction from 119.6 \$/MWhr (reference Case 10) to 101.6 \$/MWhr (LB-2 option).

The very first step of 5.3 \$/MWhr LCOE reduction comes from the superior performance and significantly reduced utility requirements required when the BASF OASE® blue solvent is used in otherwise unchanged PCC plant design and operating parameters relative to the DOE_2007 study, which is consistent with already demonstrated improvement of the net plant efficiency (Exhibit 5-4).

The next LCOE step reduction of 6.4 \$/MWhr is a result of Linde-BASF significantly lower cost of PCC plant as a result of a superior design, as already discussed and quantified in Section 5.3

The third LCOE reduction step of 4.2 \$/MWhr is a result of optimized PCC plant design and operating parameters, including solvent regeneration at higher pressure (3.4 Bara) with water condensation at lower temperature (20^oC), which significantly reduces power for CO_2 compression, along with optimized solvent circulation rates and heat management.

The final LCOE reduction step of 2.2 \$/MWhr, caused by implementing the integration of heat and power between the PC power plant and PCC plant, is somewhat smaller in the relative magnitude than the corresponding increase in plant efficiency shown in Exhibit 5-4 due to the incurred additional costs for the waste heat recovery heat exchanger, the interstage heater, and the back pressure turbine generators used. Nevertheless, their combined effect on reduced LCOE for additional more than 2 \$/MWhr certainly justifies its implementation.

The LCOE values of the two presented Linde-BASF options of 103.8 and 101.6 $/MWhr (for LB-1 and LB-2, respectively) clearly demonstrate significantly reduced penalties for CO_2 capture relative to the NETL-Case 10 of 119.6 $/MWh (calculated, for comparison purposes, on a consistent bases of 4.05 $/MWh for CO_2 TSM, as required by DOE for this techno-economic study).

Relative to the LCOE value of 64.0 $/MWhr for a PC power plant without PCC option (Case 9 of NETL-2007 Study [Ref. 1]), the utilization of Linde-BASF advanced PCC technology leads to the incremental LCOE increase of 62.2% and 58.8% for LB-1 and LB-2 options, respectively.

5.5. Sensitivity Analyses

The sensitivity of LCOE values to different methodologies of calculating the TPC and TSM costs are presented in the following few exhibits.

The LCOE values for different PCC options shown in Exhibit 5-17 only slightly differ from those shown in Exhibit 5-16; they rather confirm similarly the benefits of Linde-BASF technology on the LCOE penalties for the carbon capture and storage of 61.3% and 58.1% for options LB-1 and LB-2 versus reference Case 9 of NETL_2007 study [Ref. 1] without CO_2 capture.

The detailed breakdown of major LCOE cost elements (TPC Charges, Fuel Cost, Variable Operating Cost, Fixed Operating Cost, and CO_2 TSM) for a couple of selected cases is shown in Exhibits 5-18 and 5-19. The two major contributors are annual capital charge and fuel costs. As it is obvious, the cost element for the fuel is directly proportional to the overall energy reductions (coal consumptions) due to the utilization of advanced Linde-BASF PCC technology options, already illustrated in Exhibits 5-2 and 5-3. The reduction of the capital cost charges is a result of superimposed effects of reduced cost of Linde-BASF PCC plant, as well as of the reduced size of the entire power plant due to significantly reduced coal combustion (-11.2% and -15.3% for LB-1 and LB-2 options with respect to reference NETL Case 10), and consequently of the steam, power, and CO_2 productions. Variable operating costs for LB-1 and LB-2 options versus reference Case 10 reduce somewhat less than proportionally to the reduced coal combustion due to the higher cost of the advanced BASF solvent, as indicated in Exhibit 5-13.

As illustrated in Exhibits 5-18 and 5-19 and summarized in Exhibit 5-20, the different methodologies of estimating the TPC and/or cost for CO_2 TSM lead to slightly changed results, but estimated variations in LCOE values for each of the PCC options are within approximately 1%.

Exhibit 5-17: Incremental LCOE reduction steps (MP-S methodology for TPC)

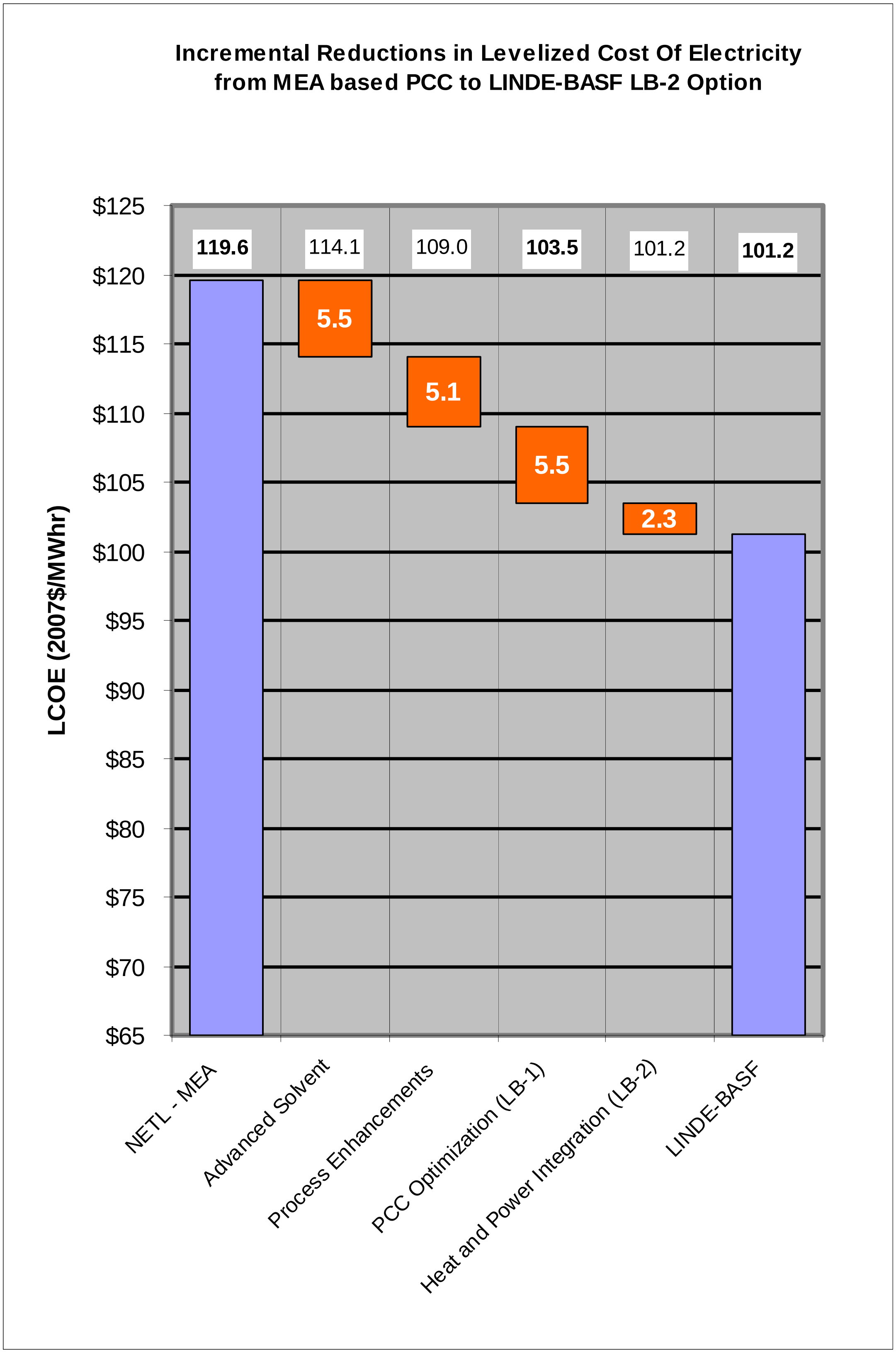


Exhibit 5-18 LCOE components for different PCC options (MP-S methodology for TPC; CO_2 TSM=4.05 \$/ton)

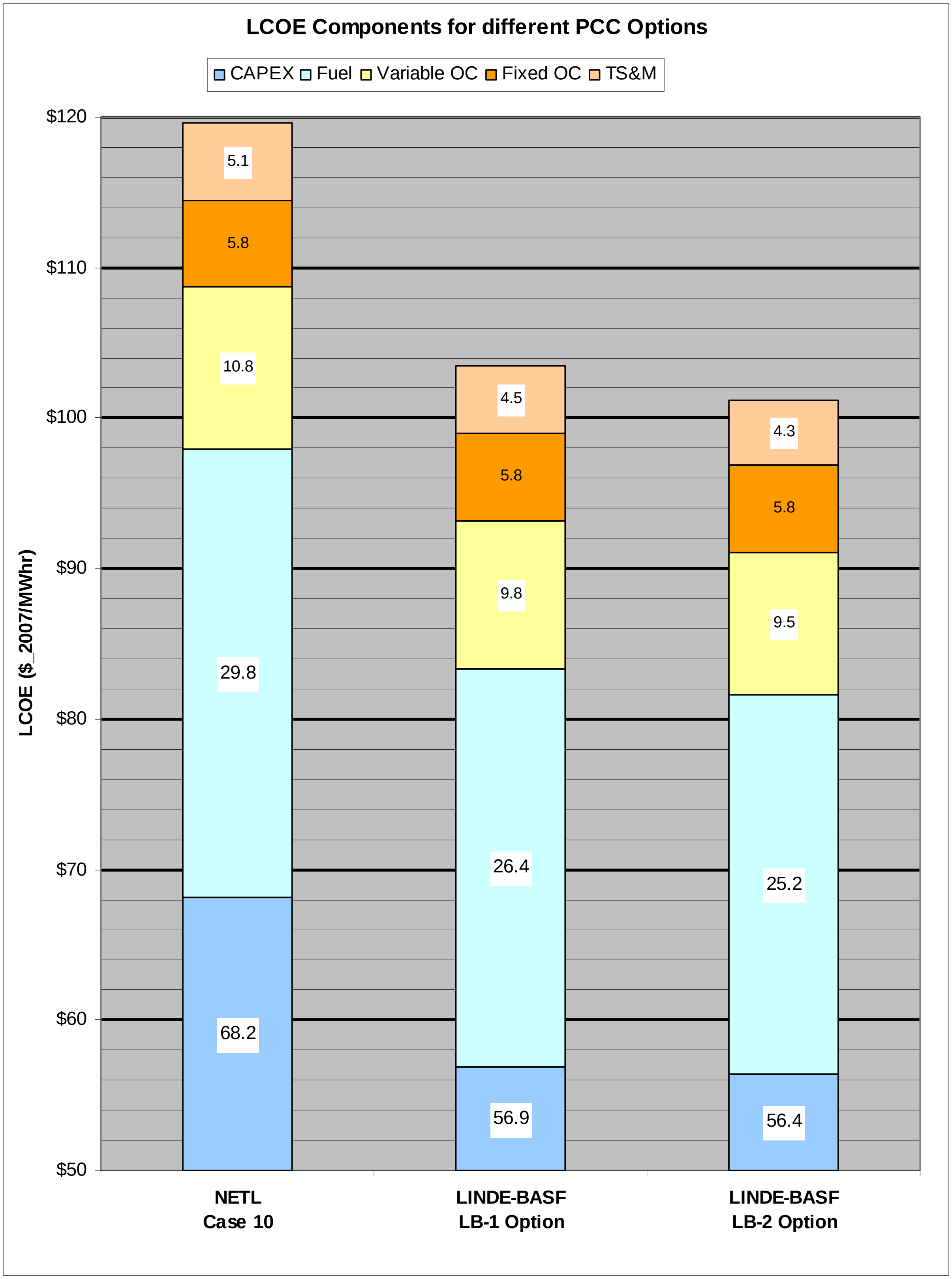


Exhibit 5-19 LCOE components for different PCC options (SP-S methodology for TPC; CO_2 TSM=4.30 $/MWhr)

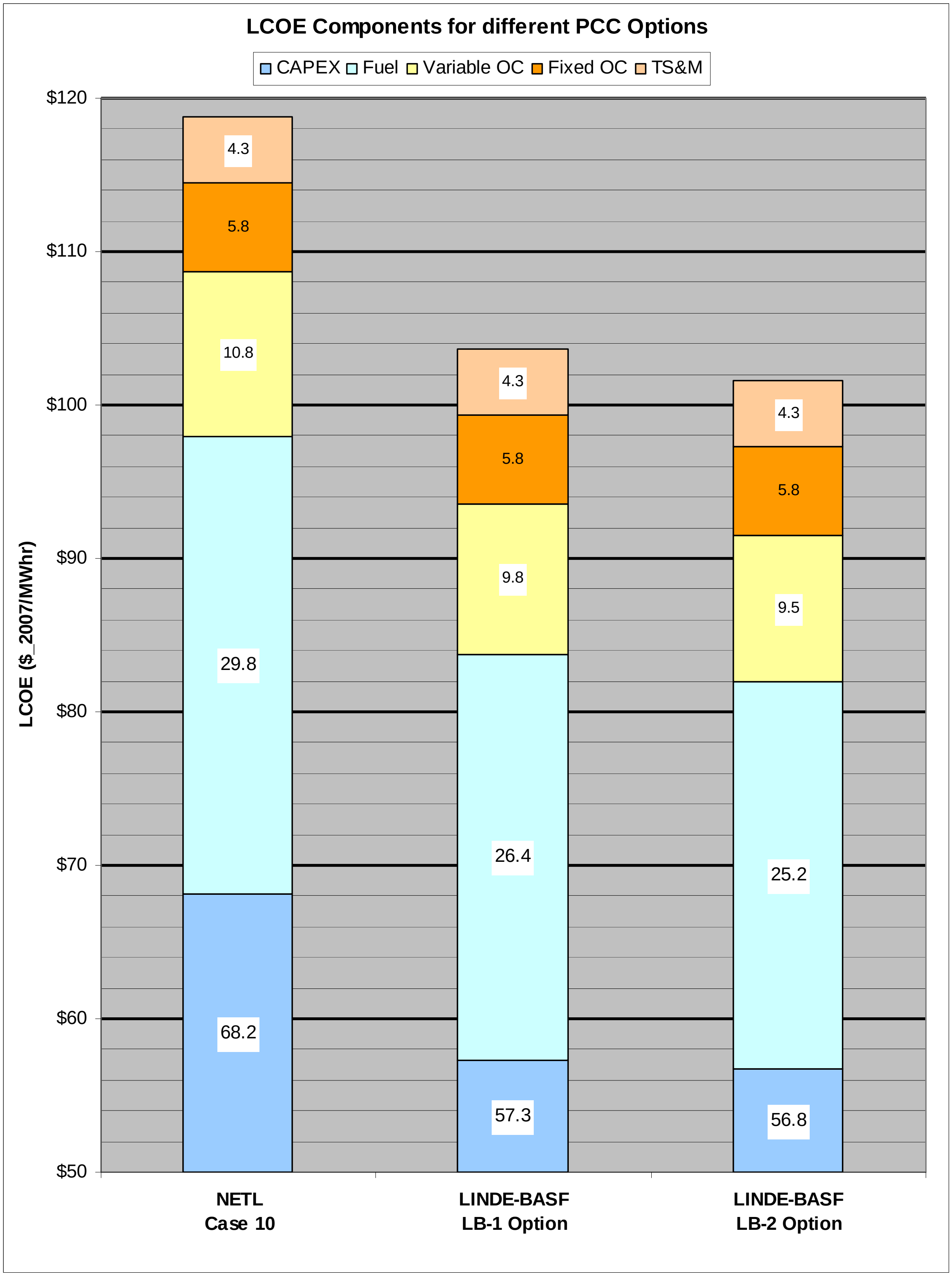


Exhibit 5-20 Estimated LCOE variations

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

6. Conclusion

A rigorous simulation model to accurately predict material and energy balances, as well as power production and auxiliary consumptions for a 550 MWe subcritical PC power plant integrated with selected PCC technology options has been developed and verified against published results from the DOE-NETL-2007 reference study [Ref. 1].

A comprehensive set of simulations of different options for the post-combustion capture and compression of 90% of produced CO_2 from a 550 MW PC power plant was performed. The performance results obtained confirm the superior performance of Linde-BASF PCC technology, compared with reference Case 10 [Ref. 1]. Specific utility energy requirements (reboiler heating duty, cooling duty) for the PCC plant with the LB-1 and LB-2 process options are more than 25% lower than for MEA-based technology, and the utility electrical power is as much as 60% lower when Linde-BASF process option LB-2 is utilized (Exhibit 5-2). These savings translate to an impressive reduction (25 - 47%) of incremental energy for CO_2 capture and compression from the 550 MW power plant when compared with baseline Case 10 (Exhibit 5-3).

The Linde-BASF PCC technology options, integrated with a 550 MWe subcritical PC power plant, lead to increased net power plant efficiency from 24.9% reported in reference Case 10 to 28.0% (LB-1) and to 29.4% (LB-2) (Exhibit 5-4).

The increased efficiency and the innovative, cost-effective design of the Linde-BASF PCC plant, lead to significant reductions of total PCC plant cost (of 34.6% for the LB-1 option and 30.4% for the LB-2 option) when compared with reference MEA-based technology (Exhibit 5-13)

The calculated LCOE for a 550 MW PC power plant with CO_2 capture and compression is 14.8 $/MWh to 18.0 $/MWh lower than in Case 10 (Exhibits 5-16 and 5-17).

Calculated LCOE values of 103.8 $/MWhr and 101.6 $/MWhr for LB-1 and LB-2 options while utilizing SP-S methodology for TPC estimates are equivalent of incremental LCOE increase for carbon capture and storage of 62.2% (LB-1) and 58.8% (LB-2) relative to the 64.0 $/MWh estimated for a 550 MW power plant without CO_2 capture. When MP-S methodology is used for TPC estimates, the resulting incremental increase in LCOE values for carbon capture and storage is 61.3% for LB-1 and 58.1% for LB-1 process option.

Appendices

- ***Revision History***

REV	DESCRIPTION	DATE	RELEASED BY	APPROVED BY
0	Initial submission to NETL	03-09-2012	SJ	KRK
1	Included all clarifications requested by DOE-NETL	05-04-2012	SJ & KRK	APJ

- ***Abbreviations***

aMWh	annual net MegaWatt-hours of power generated at 100 percent capacity factor
CCF	Capital Charge Factor for a levelized period of 20 years
CF	plant Capacity Factor (0.85 in this study)
DCC	Direct Contact Cooler
FGD	Flue Gas Desulfurization
LB-1	Linde-BASF PCC option 1 - optimized PCC plant
LB-2	Linde-BASF PCC option 2 - optimized PCC plant integrated with waste heat recovery from the power plant
LCOE	Levelized Cost Of Electricity over 20 years, mills/kWh (equivalent of $/MWh)
LF_{Fi}	Levelization Factor for category *i* Fixed operating cost
LF_{Vi}	Levelization Factor for category *i* Variable operating cost
MP-S	Multiple Parameter Scaling methodology for TPC estimates
OC_{Fi}	category *i* Fixed Operating Cost for the initial year of operation (but expressed in "first-year-of-construction" year dolar)
OC_{Vi}	category *i* Variable Operating Cost for the initial year of operation (but expressed in "first-year-of-construction" year dollar)
PCC	Post Combustion Capture
SP-S	Single Parameter Scaling methodology for TPC estimates
TPC	Total Plant Cost, $

- ***List of Exhibits***

- ***References***

[1] "Cost and Performance Baseline for Fossil Energy Plants – Volume 1: Bituminous Coal and Natural Gas to Electricity", DOE/NETL-2007/1281 Study, Final Report, Rev. 1, (May 2007)

[2] "Cost and Performance Baseline for Fossil Energy Plants – Volume 1: Bituminous Coal and Natural Gas to Electricity", DOE/NETL-2007/1281 Study, Final Report, Rev. 2, (November 2010)

[3] G. Sieder, A. Northemann, T. Stoffregen, B. Holling, P. Moser, S. Schmidt, "Post Combustion Capture Technology: Lab scale, Pilot scale, Full-scale Plant", SOGAT Abu Dhabi, U.A.E ., (March/April 2010)

[4] S. Jovanovic, R. Krishnamurthy, "Waste Heat Utilization for Energy Efficient Carbon Dioxide Capture", Linde NOI # IA0242, 2011; USPTO Provisional Patent Application, Docket No P12A004, 2012

[5] S. Jovanovic, R. Krishnamurthy, "Optimized Integration between Power Generation and Post Combustion Capture Plants", Linde NOI # IA0241, 2011; USPTO Provisional Patent Application, Docket No P12A003, 2012

- ***Model Validation***

The validation of the modeling approach described in Section 5.1 was presented in a form of detailed material and energy balances calculated for NETL_2007 reference Case 10 in the following two exhibits.

Stream Properties	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)	168,455	168,455	51,747	51,747	3,894	0	0	237,022	0	237,022	237,022	8,224	40,959	2,852	23,334
V-L Flowrate (lb/hr)	4,860,854	4,860,854	1,493,204	1,493,204	112,369	0	0	7,050,264	0	7,050,264	7,050,264	148,161	737,876	82,291	420,371
Solid Flowrate (lb/hr)	0	0	0	0	0	646,547	12,543	50,172	50,172	0	0	64,776	0	0	104,734
Temperature (F)	59	67	59	77	59	59	350	350	350	350	371	59	59	59	135
Pressure (psia)	14.7	15.3	14.7	16.1	14.5	14.7	14.4	14.4	14.4	14.2	15.3	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	-1,064.5	-6,820	-6,819.7	-41.9	-6,771.1
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	61.35
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

Stream Properties	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26
V-L mol. fract.	1	1	0	1	1	1	0	0	1	1	1
Ar	0.0079	0.0000	0.0000	0.0000	0.0000	0.0106	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.1320	0.0000	0.0000	0.9925	0.9998	0.0177	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	0.1716	1.0000	1.0000	0.0073	0.0000	0.0464	1.0000	1.0000	1.0000	1.0000	1.0000
N2	0.6651	0.0000	0.0000	0.0001	0.0001	0.8937	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0235	0.0000	0.0000	0.0000	0.0000	0.0315	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
HCl	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
V-L Flowrate (lbmol/hr)	264,279	110,738	110,738	77,150	31,386	196,676	147,556	303,802	303,802	279,921	279,921
VL Flowrate (lb/hr)	7,557,801	1,994,958	1,994,958	1,389,857	1,381,200	5,523,934	2,658,239	5,473,024	5,473,024	5,042,810	5,042,810
Solid Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0
Temperature (F)	135	743	368	69	89	89	102	484	1,050	690	1,050
Pressure (psia)	14.7	167.7	380.0	23.5	2,215.0	14.7	400.0	3,100.5	2,414.7	620.5	555.7
Enthalpy (Btu/lb)	-1,390.4	-5,448.8	-6,505.7	-3,860.8	-3,951.0	-276.0	-6,776.1	-6,376.7	-5,353.2	-5,501.6	-5,300.6
Density (lb/ft3)	0.07	0.24	54.97	0.18	51.19	0.07	62.03	50.93	2.98	0.98	0.63
Molecular Weight	28.60	18.02	18.02	18.02	44.01	28.09	18.02	18.02	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

Exhibit A-1 M&E Balances for NETL-2007 reference Case 10 (in reference to Exhibit 4-1)

Stream Properties	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Flow (lb/hr)	5,473,024	5,473,024	5,042,810	5,042,810	2,428,704	220,438	1,994,958	2,001,781	220,438	2,658,239	2,658,239	2,658,250	2,658,250	2,658,250	2,658,250
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	103.0	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

Stream Properties	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30
Flow (lb/hr)	2,658,250	5,473,024	5,473,024	5,473,024	5,046,587	385,929	251,812	182,086	68,864	160,955	89,824	111,265	9,096	3,985	2,800
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	707.9	707.9	707.9
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	-5,730	-5,466	-5,466	-5,466

Stream Properties	S31	S32	S33	S34	S35	S36	S37	S38	S39	S40
Flow (lb/hr)	2,311	385,924	637,729	68,864	229,819	319,643	430,908	433,687	1,994,958	28,535
Temperature (F)	707.9	434.2	380.8	267.7	200.5	162.4	113.0	113.0	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)	-5,466	-6,434	-6,492	-6,610	-6,678	-6,716	-6,766	-6,765	-6,506	-5,381

Total ST Electrical Power:	679.9	MW
Net Electrical Power:	549.6	MW
Net Efficiency:	24.9%	%

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

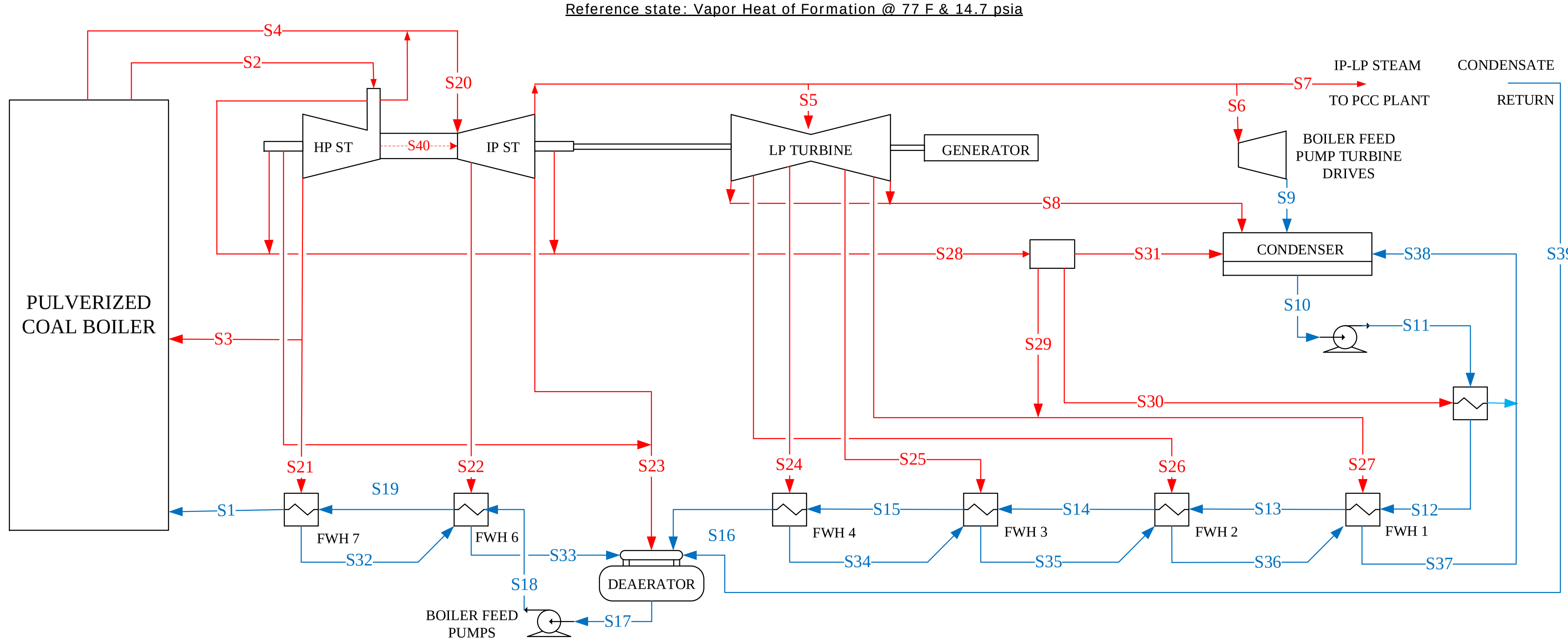


Exhibit A-2 Heat and Mass Balance: DOE/NETL-2007 Case 10 with MEA based PCC