Development of a Novel Gas Pressurized Stripping Process-Based Technology for CO_2 Capture from Post-Combustion Flue Gases

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Principal Investigator: Shiaoguo (Scott) Chen, Ph.D.

Carbon Capture Scientific, LLC
DUNS Number: 832702588
P.O. Box 188
South Park, PA 15129
412 854 6713

Submitted to
U. S. Department of Energy
National Energy Technology Laboratory

Project Manager: Timothy Fout
Email: timothy.fout@netl.doe.gov

Submission Date: October 30, 2012

Signature:

Shiaoguo (Scott) Chen, Ph.D.
CEO / President Carbon Capture Scientific, LLC

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Under the DOE's Innovations for Existing Plants (IEP) Program, Carbon Capture Scientific, LLC (CCS) is developing a novel gas pressurized stripping (GPS) process to enable efficient post-combustion carbon capture (PCC) from coal-fired power plants. A technology and economic feasibility study is required as a deliverable in the project Statement of Project Objectives. This study analyzes a fully integrated pulverized coal power plant equipped with GPS technology for PCC, and is carried out, to the maximum extent possible, in accordance to the methodology and data provided in ATTACHMENT 3 – Basis for Technology Feasibility Study of DOE Funding Opportunity Number: DE-FOA-0000403.

The DOE/NETL report on "*Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity* (Original Issue Date, May 2007), NETL Report No. DOE/NETL-2007/1281, Revision 1, August 2007" was used as the main source of reference to be followed, as per the guidelines of ATTACHMENT 3 of DE-FOA-0000403. The DOE/NETL-2007/1281 study compared the feasibility of various combinations of power plant/CO_2 capture process arrangements. The report contained a comprehensive set of design basis and economic evaluation assumptions and criteria, which are used as the main reference points for the purpose of this study. Specifically, Nexant adopted the design and economic evaluation basis from Case 12 of the above-mentioned DOE/NETL report. This case corresponds to a nominal 550 MWe (net), supercritical greenfield PC plant that utilizes an advanced MEA-based absorption system for CO_2 capture and compression.

For this techno-economic study, CCS' GPS process replaces the MEA-based CO_2 absorption system used in the original case. The objective of this study is to assess the performance of a full-scale GPS-based PCC design that is integrated with a supercritical PC plant similar to Case 12 of the DOE/NETL report, such that it corresponds to a nominal 550 MWe supercritical PC plant with 90% CO_2 capture. This plant has the same boiler firing rate and superheated high pressure steam generation as the DOE/NETL report's Case 12 PC plant. However, due to the difference in performance between the GPS-based PCC and the MEA-based CO_2 absorption technology, the net power output of this plant may not be exactly at 550 MWe.

2.1 POWER PLANT DESIGN CRITERIA

2.1.1 General

The design PC power plant used in this study is a supercritical steam-electric generating power plant with carbon capture to generate a nominal 550 MWe on a net basis, consistent with the DOE/NETL-2007/1281 report's Case 12 supercritical PC plant with CO_2 capture. The gross output of the plant is about 663 MWe. The steam generator for the supercritical PC plant is a drum wall-fired, totally enclosed dry bottom boiler, with superheater, reheater, economizer and air-heater. The steam turbine generator (STG) is operating at throttle conditions of 3,500 psig /1,100 °F/1,100 °F, and with surface condenser operating at ~2 inch Hg using 60 °F cooling water that is available to the power plant.

The plant is designed for NOx reduction using a combination of low-NOx burner and overfire air as well as with the installation of a selective catalytic reduction (SCR) system. It is also designed for particulate control with baghouse and a wet limestone based flue gas desulfurization (FGD) system for sulfur removal. This combination of pollution control technologies result in a significant co-benefit capture of mercury. The mercury co-benefit capture is assumed to be 90% for this combination, sufficient to meet current mercury emissions limits, hence no activated carbon injection is included in this case.

The plant is considered to operate as a base-loaded unit but with consideration for daily or weekly cycling. Annual capacity factor is 85 percent or 7,450 hrs/year at full capacity

2.1.2 Site-Related Conditions

The supercritical PC plant in this study is assumed to be located at a generic plant site in Midwestern USA, with site-related condition as shown below:

- Location — Midwestern USA
- Elevation, ft above sea level — 0
- Topography — Level
- Size, acres — 300
- Transportation — Rail
- Ash/slag disposal — Off Site
- Water — Municipal (50%)/Groundwater (50%)
- Access — Landlocked, having access by train and highway
- CO_2 disposition — Compressed to 2,200 psig at battery limit before

being transported 50 miles for sequestered in a saline formation at a depth of 4,055 ft (Study scope limited to delivery at battery limit only)

2.1.3 Meteorological Data

Maximum design ambient conditions for material balances, thermal efficiencies, system design and equipment sizing are:

• Atmospheric pressure, psia	14.7
• Dry bulb temperature (DBT)	59 °F
• Wet bulb temperature (WBT)	51.5 °F
• Ambient relative humidity, %	60

2.1.4 Technical Assumptions and Data

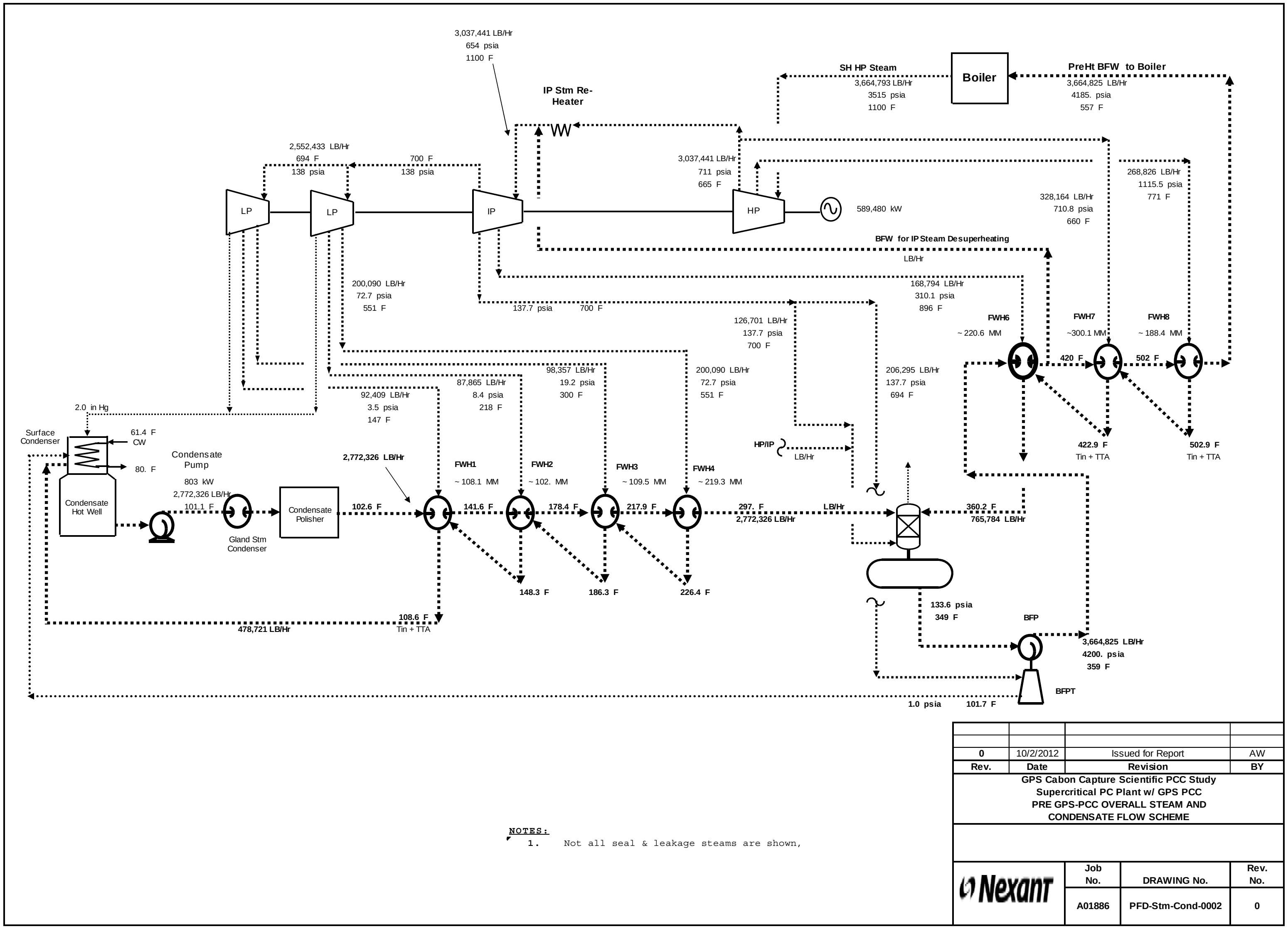
Other technical data and assumptions include:

- Design coal feed to the power plant is Illinois No. 6 with characteristics presented in Table 2-1. The coal properties are from NETL's Coal Quality Guidelines.
- Selected flows and operating conditions for the turbine are listed below:

Turbine gross power output, MW	663
SH HP steam inlet flow, 1000 lbs/hr	5,241
HP turbine inlet pressure, psig	3,500
HP turbine inlet temperature, °F	1,100
HP turbine outlet pressure, psig	696
IP turbine inlet pressure, psig	639
IP turbine inlet temperature, ^{o}F	1,100
IP turbine outlet pressure, psig	123
LP turbine inlet pressure, psig	123
Surface condenser pressure, inches Hg	2.0
Deaerator pressure, psig	119

For this study, a GateCycle^{TM} model of the steam cycle is developed and calibrated against the 2007 DOE/NETL report to define the reference supercritical PC power plant steam cycle characteristics. See Figure 2-1 for a summary of the calibrated output. To estimate the power plant performance for the different potential PCC cases for the project, the low pressure turbine and condenser section of the calibrated GateCycle^{TM} model is modified to meet the specific steam extraction required by each PCC scheme.

Figure 2-1
Pre-PCC Steam and Condensate Flow Scheme



- To generate the 5,241,000 lb/hr of SH HP steam to the STG, the boiler will burn 586,627 lb/hr, or 6,845 MMBtu (HHV)/hr of as-received Illinois No. 6 coal as listed in Table 2-1. The boiler firing rate and the SH HP steam generation will be held constant for all PCC cases.

Table 2-1
Illinois No. 6 Coal Specification

Rank	Bituminous
Seam	Illinois #6 (Herrin)
Source	Old Ben Mine
Ultimate Analysis (as received), weight%	
Carbon	63.75
Hydrogen	4.50
Nitrogen	1.25
Chlorine	0.29
Sulfur	2.51
Oxygen	6.88
Ash	9.70
Moisture	11.12
Total	100.0
Proximate Analysis (as received), weight%	
Volatile Matter	34.99
Fixed Carbon	44.19
Ash	9.70
Moisture	11.12
Total	100.0
HHV (Btu/lb)	11,666

- Auxiliary loads for the overall plant can be separated into three categories: PCC-independent PC aux loads, PCC-dependent PC aux loads, and PCC loads. PCC-independent PC aux loads total 28,330 kWe, according to the following breakdowns:

	kWe
Coal Handling & Conveying	490
Limestone Handling & Reagent Preparation	1,270
Pulverizer	3,990
Ash Handling	760
Primary Air Fans	1,870
Forced Draft Fans	2,380
Induced Draft Fans	10,120
SCR	70
Baghouse	100
FGD Pumps and Agitators	4,250
Condensate Pumps	630
Steam Turbine Auxiliaries	400

Miscellaneous BOP	2,000
Total PCC-independent PC aux loads	28,330

PCC-dependent PC aux loads include cooling water (CW) circulation pump loads, cooling tower (CT) fan loads, and transformer loss. PC CW and CT loads are proportional to the STG surface condenser duty which varies depending on the PCC steam extraction requirement. Transformer loss is proportional to STG gross power output which also varies with PCC steam extraction requirement.

PCC loads will vary depending on the PCC design and include power consumed in the CO_2 capture and compression processes, plus any new CW and CT consumptions due solely to the PCC cooling loads.

- It is assumed that the supercritical PC utilizes a mechanical draft, evaporative cooling tower, and all process blowdown streams are assumed to be treated and recycled to the cooling tower. The design ambient wet bulb temperature of 51.5 °F is used to achieve a cooling water temperature of 60 °F using an approach of 8.5 °F. The PC cooling water range is assumed to be 20°F. The cooling tower makeup rate was determined using the following:

  Evaporative losses of 0.8% of the circulating water flow rate per 10 °F of range

  Drift losses of 0.001% of the circulating water flow rate

  Blowdown losses are calculated as follows:

  Blowdown Losses = Evaporative Losses/(Cycles of Concentration - 1)

  where cycles of concentration is a measure of water quality, and a mid-range value of 4 is chosen for this study

- Raw water makeup was assumed to be provided 50% by a publicly owned treatment works and 50% from groundwater.

2.1.5 Environmental/Emissions Requirements

Design emissions requirements and limits for the supercritical power plant with PCC in this study are as follow:

- SO_2 0.085 lb/MMBtu
- NOx 0.070 lb /MMBtu as NO_2
- Particulate Matter (Filterable) 0.013 lb/MMBtu
- Hg 1.14×10^{-6} lb/MMBtu
- VOC 0.0025 lb/MMBtu

2.1.6 Site Specific Requirements

Although the following design parameters are considered site-specific, and are not quantified for this study, allowances for normal conditions and construction are included in the cost estimates.

- Flood plain considerations

- Existing soil/site conditions
- Water discharges and reuse
- Rainfall/snowfall criteria
- Seismic design
- Buildings/enclosures
- Fire protection
- Local code height requirements
- Noise-regulations – Impact on site and surrounding area

2.2 PCC DESIGN CRITERIA

Guidelines for the PCC plant design include the following:

2.2.1 GENERAL

The PCC plant is designed as an integral part of the supercritical PC plant to recover up to 90% of the CO_2 in the flue gas. For the supercritical PC plant with CO_2 capture, it is assumed that all of the fuel carbon is converted to CO_2 in the flue gas. CO_2 is also generated from limestone in the FGD system, and 90% of the total CO_2 exiting the FGD absorber is subsequently captured in the PCC.

The projected largest-single train size equipment will be used to maximize economy-of-scale. Vessels exceeding transportation size limits (as specified in the Project Transportation Size Limitation section of this document) will be field fabricated. The equipment is designed for a 30-year plant life.

Rotating equipment critical to the continuous plant operation is spared. Where sparing is not feasible, alternate operation will be identified to maintain continuous power plant operation.

2.2.2 FLUE GAS FEED SPECIFICATION

The PC plant boiler will be burning 586,627 lb/hr, or 6,845 MMBtu(HHV)/hr of as-received Illinois No. 6 coal to generate 5,241,000 lb/hr of SH HP steam to the STG, as per the Case 12 supercritical PC plant in the 2007 DOE/NETL report. Flue gas exiting the wet FGD before the vent stack is the design feed for the PCC plant. The corresponding flue gas feed composition and flow rate to the PCC plant is as shown below:

Composition, Vol. %:

N_2 (include Argon)	67.70
CO_2	13.26
O_2	2.35
H_2O	16.68 (by difference)
Emission components (see below)	0.01
Total Vol. %	100.00

Total gas volumetric flow rate, SCF/Hr	90,493,000 (calculated)
Total gas molar flow rate, lbmoles/hr	238,453
Total gas mass flow rate, lbs/hr	6,833,360
Temperature, °F	135
Pressure, psia	15.2

The estimated emission component flows included in the flue gas feed are assumed to be at the emission specifications listed in Section 2.1.5, and are as follows:

NO (assume 95 vol% of NOx)	297 lb/hr (max)
NO_2 (assume 5 vol% of NOx)	24 lb/hr (max)
SO_2	582 lb/hr (max)
$PM_{Filterable}$	89 lb/hr (max)

Emission component NO_2, and SO_2 can potentially be further removed from the flue gas through non-reversible reactions with the amine solvent used. NO and Hg are assumed to pass through the PCC recovery unit and released to the atmosphere with the treated flue gas. PM is assumed to be removed from the flue gas through water and amine solvent scrubbing.

2.2.3 DESIGN PRODUCT SPECIFICATIONS

2.2.3.1 CO_2 Product Specifications

Recovered CO_2 is delivered at the battery limit (B/L) with the following specifications:

Inlet pressure, psig	2,200
Inlet temperature, °F	79
N_2 + Ar concentration, ppmv	< 1000 (revised for PCC processes)
O_2 concentration, ppmv	< 100 (revised for PCC processes)
H_2O, ppmv	< 50 (revised for mol sieve drying)

2.2.4 UTILITY COMMODITY SPECIFICATIONS

2.2.4.1 Low Pressure Steam

Low pressure (LP) steam for PCC stripper reboiling can be extracted from the power plant to meet the following PCC B/L conditions:

Min pressure, psia	As Required
Temperature, °F	Sat + 10

LP steam, if needed, is assumed to be desuperheated to 10 °F above saturation temperature to allow positive control of desuperheater condensate injection. Degree of LP steam superheat can be varied to meet minimum desuperheater design requirement.

2.2.4.2 Intermediate Low Pressure Steam

Intermediate low pressure (ILP) steam for amine reclaiming, if needed, can be extracted intermittently from the power plant at the following B/L conditions:

Min pressure, psia	As Required
Temperature, °F	Sat + 10
Equivalent frequency, % of time	~ 15%

The ILP steam is assumed to be desuperheated to 10 °F above saturation temperature to allow positive control of desuperheater condensate injection. Degree of ILP steam superheat can be varied to meet minimum desuperheater design requirement.

2.2.4.3 Return Condensate

Reboiler steam condensate will be pumped back to the power plant hot at the following conditions:

Min pressure, psia	175
Temperature, °F	TBD by PCC Design

2.2.4.4 Cooling Tower Water

Cooling water from the new PCC cooling towers is available at the following conditions:

Maximum supply temperature, °F	60
Maximum return temperature, °F	100
Maximum supply pressure, psia	70
Maximum PCC pressure drop, psi	30

2.2.4.5 Power Plant Condensate for Waste Heat Recovery

Condensate from the power plant surface condenser hotwell is available, downstream of the condensate polisher, for waste heat recovery (WHR) in the PCC plant. Relevant condenser and condensate system parameters are indicated below:

Condenser inlet cooling water temperature, °F	60
Condensate maximum supply temperature, °F	80
Cond flow at 6,845 MMBtu/hr firing, 10^6 lbs/hr	3.95
Maximum cond available for WHR, 10^6 lbs/hr	3.2
Minimum condensate pressure* before Deaerator, psia	130
Maximum PCC pressure drop, psi	30

* PCC plant heat source pressure, when containing amine compounds or CO_2, should be at least 30 psi lower than the minimum condensate pressure to avoid contaminating the condensate to the deaerator from heat exchanger leakage.

2.2.5 Process Water Streams

2.2.5.1 Excess Process Water

The PCC plant is designed to minimize/eliminate discharging hydrocarbon solvent-containing waste waters.

Process purge water from scrubbing the WFGD flue gas feed has no hydrocarbon solvent and will be recycled as makeup water to the new cooling tower system. If necessary, this feed scrubber purge water can be filtered and recycled as feed to the new demineralizer unit to minimize well water consumption.

2.2.6 PROJECT TRANSPORTATION SIZE LIMITATIONS

2.2.6.1 Overland Transportation Size

The maximum overland transportable dimension is 100 feet long by 15 feet wide by 15 feet height (including carriage height). Maximum equipment height is 13.5 feet assuming using 1.5 feet height low boy carriage. Maximum overland transportable weight is 120 tons.

2.3 COST ESTIMATION METHODOLOGY

The Total Plant Cost (TPC) and Operation and Maintenance (O&M) costs for the supercritical PC power plant and the associated CO_2 capture plant are estimated by Nexant as described in this section. The estimates will be based on 2007 costs, per ATTACHMENT 3 of the FOA.

2.3.1 CAPITAL COST

The DOE/NETL report provided a cost estimate for 14 major subsystems of the Case 12 supercritical PC plant with CO_2 capture. Using this as the reference cost estimate, modifications to each subsystem were made either by capacity factoring or by direct replacement with Nexant's own estimates in order to obtain the overall cost estimate for the nominal 550 MWe supercritical PC plant with GPS-based PCC. For the subsystems in which capacity factoring was used to perform the cost estimates, a power factor of 0.7 was applied.

The list of the Case 12 supercritical PC plant subsystems and bases for modifications are shown in Table 2-2.

Table 2-2
Cost Estimate Basis for Supercritical PC Plant with CO_2 Capture

Acct No.	Item/Description	Cost Estimate Basis	Capacity Factor Reference Basis (DOE/NETL Report Case 12)
1	COAL & SORBENT HANDLING	Capacity Factor	AR Coal
2	COAL & SORBENT PREP & FEED	Capacity Factor	AR Coal
3	FEEDWATER & MISC. BOP SYSTEMS		
3.1	Feedwater System	Capacity Factor	AR Coal
3.2	Water Makeup & Pretreating	Capacity Factor	CW Makeup
3.3	Other Feedwater Subsystems	Capacity Factor	AR Coal
3.4	Service Water Systems	Capacity Factor	AR Coal
3.5	Other Boiler Plant Systems	Capacity Factor	AR Coal
3.6	FO Supply Sys & Nat Gas	Capacity Factor	AR Coal
3.7	Waste Treatment Equipment	Capacity Factor	AR Coal
3.8	Misc Equipment (Cranes, Air Comp, etc)	Capacity Factor	AR Coal
4	PC BOILER	Capacity Factor	AR Coal
5	FLUE GAS CLEANUP	Capacity Factor	AR Coal
5B	CO_2 REMOVAL & COMPRESSION		
5B.1	CO_2 Removal System	Nexant Estimate	N/A
5B.2	CO_2 Compression & Drying	Nexant Estimate	N/A
6	COMBUSTION TURBINE/ACCESSORIES	N/A	N/A
7	HRSG, DUCTING & STACK	Capacity Factor	AR Coal
8	STEAM TURBINE GENERATOR		
8.1	Steam TG & Accessories	Capacity Factor	STG Output
8.2	Turbine Plant Auxiliaries	Capacity Factor	STG Output
8.3	Condenser & Auxiliaries	Capacity Factor	Cond Duty
8.4	Steam Piping	Capacity Factor	Gross Power Output
8.9	TG Foundations	Capacity Factor	Gross Power Output
8.10	Back Pressure TG & Accessories	Capacity Factor	BPTG Output
9	COOLING WATER SYSTEM		
9.1	Cooling Tower	Capacity Factor	CT Load
9.2	Circulating CW Pump	Capacity Factor	CT Load
9.3	Circulating CW Syst Aux	Capacity Factor	CT Load
9.4	Circulating CW Piping	Capacity Factor	CT Load
9.5	Makeup Water System	Capacity Factor	CW Makeup
9.6	Closed CW System	Capacity Factor	CCW Load
9.9	Circ CW Syst Foundations & Structures	Capacity Factor	CT Load
10	ASH/SPENT SORBENT HANDLING SYS	Capacity Factor	AR Coal
11	ACCESSORY ELECTRIC PLANT	Capacity Factor	Gross Power Output
12	INSTRUMENTATION & CONTROL	Capacity Factor	AR Coal
13	IMPROVEMENT TO SITE	Capacity Factor	AR Coal
14	BUILDING & STRUCTURES	Capacity Factor	AR Coal

2.3.1.1 Supercritical PC Plant

The capital cost estimates for the supercritical PC section of the overall plant are developed based on the Case 12 costs provided in the DOE/NETL report.

The PCC section in this study differs from the CO_2 capture section provided in the DOE/NETL report, resulting in a variation of the PC plant performance due to the differences in PCC design as well as solvent selection. As stated in Section 2.1.4, the revised PC plant with GPS-based PCC performance was estimated on GateCycle™, using the GPS PCC LP steam extraction rate, hence resulting in a different power generation rate from the DOE/NETL Case 12 supercritical PC plant. For this reason, the PC plant equipment costs (primarily for the LP steam turbine, condenser and CW/CT sections) are re-estimated on a capacity-factor basis using the DOE/NETL reported costs as a baseline reference.

Material, direct labor, engineering and construction management fees and home office cost, and contingencies consistent with those used in the DOE/NETL report Case 12 are added to come up with the total supercritical PC plant cost estimate.

2.3.1.2 PCC Plant

Capital cost for GPS-based PCC is a major equipment (ME) factored estimate for the DOE/NETL Case 12 supercritical plant with a target accuracy of ±30%. Separate estimates are prepared for the CO_2 recovery facility and the CO_2 compression facility.

For an ME-factored estimate, ME material and labor costs were developed from equipment sizes, quantities, and design parameters defined by the PCC design from CCS. Bulk material and labor costs were factored from the ME costs. The sum of the ME and bulk material costs, including shipping costs, forms the total direct cost (TDC).

Construction indirect cost, factored from total direct labor cost, is added to the TDC to come up with the total field cost (TFC). Using factors consistent with the DOE/NETL report for the Case 12 total plant cost (TPC), the Engineering and Construction Management Fees and Home office cost, and contingencies are added to the TFC to come up with the TPC.

CCS provided Nexant with the heat and material balances of the overall GPS process, modeled using ProTreat™ simulation software. Nexant is able to estimate the size for each piece of major equipment used in the GPS process based on the individual heat and material stream flows of the simulation. Exceptions to this are the absorber columns and regenerator column, whereby CCS provided the equipment sizing of these columns (diameters and packed bed heights) to Nexant for cost estimation.

Upon generating the size estimates for the individual equipment, the costs for the equipment were generated using commercial estimation software (ASPEN ICARUS) with adjustments based on past quotes for similar equipment where necessary. No new quotations specific to this PCC design were solicited. Installation labor for each ME was factored from historical data by equipment type.

Costs for bulk materials such as instrumentations, piping, structure steel, insulation, electrical, painting, concrete & site preparation associated with the major equipment were factored from

ME costs (which exclude subcontracted [S/C] item costs) based on historical data for similar services. Installation labor for each bulk commodity was factored from historical data by type.

Construction indirect cost was factored from total direct labor costs based on historical data. Construction indirect cost covers the cost for setup, maintenance and removal of temporary facilities, warehousing, surveying and security services, maintenance of construction tools and equipment, consumables and utilities purchases, and field office payrolls.

Installation labor productivity and cost (wages, fringe benefit costs & payroll based taxes and insurance premiums) used to calculate the installation costs at 2007 price levels are based on Nexant's experience and database for this location, and are identical to those used in the previous EPRI studies for this site.

2.3.1.3 Engineering and Construction Management, Home Office Fees & Contingencies

Engineering and Construction Management are estimated as a percent of TFC. These costs consist of all home office engineering and procurement services as well as field construction management costs.

Both the project contingency and process contingency costs represent costs that are expected to be spent in the development and execution of the project that are not yet fully reflected in the design. Project contingency is added to the TFC to cover project uncertainty and the cost of any additional equipment that would result during detailed design. Likewise, process contingency is added to the TFC to cover the cost of any additional equipment that would be required as a result of continued technology development. For this study, the factors used for the above fees and contingencies are consistent with those used in the DOE/NETL study.

2.3.2 O&M Costs

The O&M costs pertain to those charges associated with operating and maintaining the power plants over their expected life. These costs include:

- Operating labor
- Maintenance – material and labor
- Administrative and support labor
- Consumables
- Fuel
- Waste disposal

There are two components of O&M costs; fixed O&M, which is independent of power generation, and variable O&M, which is proportional to power generation. The variable O&M costs are estimated based on 85% capacity factor.

2.3.2.1 Labor

Operating labor cost is determined based on the number of operators required to work in the plant. Other assumptions used in calculating the total labor cost include:

- 2007 Base hourly labor rate, \$/hr $33

- Length of work-week, hrs 50
- Labor burden, % 30
- Administrative/Support labor, % O&M Labor 25
- Maintenance material + labor, % TPC 1.64
- Maintenance labor only, % maintenance material + labor 40

2.3.2.2 Consumables and Waste Disposal

The cost of consumables, including fuel, is determined based on the individual rates of consumption, the unit cost of each specific consumable commodity, and the plant annual operating hours. Waste quantities and disposal costs are evaluated similarly to the consumables.

The unit costs for major consumables and waste disposal are based on the values reported in the DOE/NETL report. These costs are escalated to 2010, the year when construction is completed and production starts.

2.4 FINANCIAL MODELING BASIS

The NETL Power Systems Financial Model (PSFM) is used for economic analysis for the current study following the same methodology as used in the NETL/DOE 2007/1281 report. This method's figure-of-merit is the levelized cost of electricity (LCOE) over a 20-year period. The NETL Power Systems Financial Model (PSFM) was developed by Nexant for DOE to calculate the LCOE for power plants.

To calculate the LCOE, the PSFM requires a variety of inputs, among those, the capital cost and O&M costs of the plant, as described in section 2.3. Other parameter assumptions required by the model include the following:

- Income tax rate, % 38
- Percentage debt, % 45
- Interest rate, % 11
- Equity desired rate of return, % 12
- Repayment term of debt, years 15
- Depreciation 20 years, 150% declining balance
- Working capital None
- Plant economic life, years 30
- Tax holiday, years 0
- Start-Up costs (% of TPC less contingencies) 2
- EPC escalation, % per year 0
- Coal price nominal escalation, % 2.35

- O&M cost nominal escalation, % 1.87
- Duration of construction, years 3
- First year of construction 2007
- Construction cost distribution, %
    - Year 1 5%
    - Year 2 65%
    - Year 3 30%

All costs are expressed in the "first-year-of-construction" year dollars, and the resulting LCOE is also expressed in "first-year-of-construction" year dollars.

The DOE/NETL report's net 550 MWe supercritical PC plant without CO_2 capture (Case 11) LCOE is to be used as the benchmark for the supercritical PC plant with CO_2 capture to compare against. The Case 11 20-year LCOE stated in the DOE/NETL report is 63.3 mills/kWh. Entering the relevant inputs from the report for this case into the Nexant PSFM model, the model returns an LCOE of 63.9 mills/kWh. The small difference (< 1%) between the DOE/NETL report and Nexant's PSFM model shows that the Nexant PSFM is consistent with the DOE/NETL standards in reporting the LCOE for power plants.

As stated earlier, the supercritical PC plant with GPS-based PCC LCOE is evaluated using the Nexant PSFM model and will be compared against the same model's result of 63.9 mills/kWh for the supercritical PC plant without CO_2 capture.

Section 3 GPS-Based PCC Design, Performance and Cost Estimate

3.1 GPS PROCESS OVERVIEW AND DESCRIPTION

CCS is responsible for the design of the GPS-based PCC process, which utilizes a proprietary solvent to absorb CO_2.

3.2 GPS-BASED PCC PERFORMANCE SUMMARY

CCS provided Nexant with the heat and material balances of the overall GPS process, modeled on ProTreat^{TM} simulation software. Based on these balances, Nexant is able to generate an overall utilities sheet that summarizes the GPS PCC process' total reboiling steam requirement and electrical consumption. The GPS process' steam consumption is used as an input to Nexant's GateCycle^{TM} model of the supercritical PC plant, as stated earlier in Section 2.1.4, to determine the gross power generated by the power plant's steam turbines.

The auxiliary loads for the overall plant are separated into three categories: PCC-independent PC auxiliary loads, PCC-dependent PC auxiliary loads, and PCC loads. The PCC-independent PC auxiliary loads are consistent with the values from the DOE/NETL report and are stated in Section 2.1.4. The electrical load from the PCC utilities summary sheet is added directly to the total auxiliary loads as the PCC load. PCC-dependent PC aux loads. Cooling water (CW) circulation pump loads, cooling tower (CT) fan loads and transformer losses vary with the PCC steam extraction requirement. These are calculated based on the PCC utilities consumption from the summary sheet and added to the total auxiliary load as the PCC-dependent PC auxiliary loads.

3.3 SUPERCRITICAL PC PLANT WITH GPS-BASED PCC PERFORMANCE SUMMARY

The net power output and efficiency of the supercritical PC plant with GPS-based CO_2 capture is 595.6 MWe and 29.7% respectively. Table 3-1 summarizes the performance and efficiency of the overall PC plant with GPS-based PCC.

Table 3-1
Supercritical PC Plant with GPS-Based PCC Performance Summary

POWER SUMMARY (Gross Power at Generator Terminals, kWe)	
TOTAL POWER, kWe:	**696,034**
AUXILIARY LOAD SUMMARY, kWe:	
Coal Handling and Conveying	490
Limestone Handling & Reagent Preparation	1,270
Pulverizers	3,990
Ash Handling	760
Primary Air Fans	1,870
Forced Draft Fans	2,380
Induced Draft Fans	10,120
SCR	70
Baghouse	100
FGD Pumps and Agitators	4,250
Miscellaneous Balance of Plant	2,000
Amine CO2 Capture Plant Auxiliaries	35,760
CO2 Compression	14,664
Steam Turbine Auxiliaries	400
Condensate Pumps	630
Cooling Water Circulation Pumps	14,917
Cooling Tower Fans	4,330
Transformer Losses	2,413
TOTAL AUXILIARIES, kWe	**100,413**
NET POWER, kWe	**595,620**
Net Plant Efficiency (HHV)	29.7%
Net Plant Heat Rate (Btu/kWh)	11,492
COOLING TOWER LOADS, MMBtu/hr:	
Surface Condenser Duty	1,879
Closed Cycle Cooling Duties	142
Amine CO2 Capture Plant Cooling Duties	2,107
CO2 Compression Cooling Duties	149
TOTAL COOLING TOWER LOADS, MMBtu/hr	**4,277**
CONSUMABLES	
As-Received Coal Feed, lb/h	586,627
Limestone Sorbent Feed, lb/h	58,054
Thermal Input (HHV), MMBtu/hr	6,845
Makeup Water, gpm	8,398
OVERALL MAKEUP WATER BALANCE, gpm	
FGD Makeup	779
BFW Makeup	105
Boiler Blowdown	(105)
CO2 Capture & Compression Makeups	240
CO2 Capture & Compression Condensate Purges	(1,171)
Cooling Tower Makeup	8,550
TOTAL, gpm	**8,398**

3.4 SUPERCRITICAL PC PLANT WITH GPS-BASED PCC LCOE

Using the methodology as described in Section 2.4, the estimated LCOE for the supercritical PC plant with GPS-based PCC, as evaluated by the Nexant PSFM and ***not including*** CO_2 transport, storage and monitoring (TS&M), is 121.4 mills/kWh. This is 190% of the LCOE of the supercritical PC plant without CO_2 capture (63.9 mills/kWh).

4.1 OVERALL PERFORMANCE, COST AND LCOE COMPARISON

Table 4-1 compares the power outputs, capital and O&M cost estimates and LCOE among the cases of interest for this study. These are namely: the DOE/NETL report Case 11 supercritical PC plant without CO_2 capture, the DOE/NETL report Case 12 supercritical PC plant with Econoamine FG+-based PCC, Nexant's independent study of a nominal 550 MWe supercritical PC plant using generic, 30 wt% MEA-based PCC, and the nominal 550 MWe supercritical PC plant using GPS-based PCC.

Table 4-1
Performance, Cost and LCOE Comparison

Levelised Cost of Energy (LCOE) Summary				
Description	Supercritical PC w/o CO2 Capture	Supercritical PC w/ CO2 Capture		
Type of CO2 Capture Technology	N/A (DOE/NETL Case 11)	Econoamine (DOE/NETL Case 12)	Generic 30wt% MEA	GPS
LCOE Estimation Model	Nexant PSFM			
Power Production, MW				
Gross Power	580	663	683	696
Net Power	550	546	558	596
Capital Cost, $MM				
Power Plant	866	1110	1111	1111
PCC Plant	0	411	377	813
CO2 Compression and Drying	0	46	121	38
Start Up Costs (2% TPC before Contingency)	15	26	27	32
Total Capital Cost, $MM	**882**	**1594**	**1636**	**1994**
Operating Cost excl Fuel, $MM/yr				
Fixed Operating Cost	13.8	20.5	20.8	23.7
Variable Operating Cost				
Non PCC related Opt Cost	20.0	33.6	34.7	37.9
NaOH		0.9	0.9	0.9
H2SO4		0.3	0.3	0.3
Amine M/U		1.0	1.1	1.1
Active Carbon		0.6	0.5	0.5
Corrosion Inhibitor/Solvent MU		0.0	0.0	0.0
Total Operating Cost excl Fuel, $MM/yr	**33.8**	**56.9**	**58.4**	**64.5**
Fuel Cost, $MM/yr	**64.5**	**92.0**	**92.0**	**92.0**
LCOE (excl CO2 TS&M), mills/kWh	**63.9**	**112.7**	**112.5**	**121.4**
% of Case 11 LCOE	**--**	**176%**	**176%**	**190%**

There is a very small difference between the LCOE estimates for the DOE/NETL report Case 12 supercritical PC plant with Econoamine FG+-based PCC and Nexant's independent model of a supercritical PC plant using generic, 30 wt% MEA-based PCC (112.7 mills/kWh vs 112.5 mills/kWh). Although the latter produces more power due to the BPST that recovers some power from the extraction steam expansion, it also incurs a higher capital cost, primarily due to larger CO_2 compression costs based on Nexant's cost estimation methods. Given that the fuel and O&M costs are largely similar, the capital cost increase cancels out the effect of greater power production hence, resulting in a very small LCOE difference between this case and the DOE/NETL report Case 12.

The net power produced in the supercritical PC plant with GPS-based PCC is 596 kW, greater than the MEA-based design. This higher efficiency is mainly due to the GPS process' lower reboiling steam requirement and lower CO_2 compression auxiliary power consumption.

The GPS-based PCC CO_2 compression section capital cost is low at $38 million, or about 31% of the MEA-based PCC CO_2 compression section due to the GPS' regeneration of CO_2 at high pressure, thus reducing the CO_2 compression requirements. However, its CO_2 capture section capital cost, at $813 million, is more than twice that of the MEA-based PCC. This is due to the costs being greater for the GPS process CO_2 absorption and high pressure CO_2 stripping columns, which are larger and operate at high pressure respectively. Also, due to an additional high pressure CO_2 absorption column and multiple CO_2 flash stages, more equipment that needs to withstand high pressure is required, further adding to the overall capital cost.

O&M costs for this case are higher as well, primarily due to costs that are factored based on the TPC. The result is that the 20-year LCOE for the supercritical PC plant with GPS-based PCC, ***not considering*** CO_2 TS&M, is 121.4 mills/kWh, or 190% of the Case 11 supercritical PC plant without CO_2 capture.

Appendix A Acronyms and Abbreviations

Ar	Argon
B/L	Battery Limit
BOP	Balance of Plant
BPST	Back Pressure Steam Turbine
Btu	British Thermal Unit
CCS	Carbon Capture Scientific, LLC
CO_2	Carbon Dioxide
CT	Cooling Tower
CW	Cooling Water
DBT	Dry Bulb Temperature
Deg F, deg F,	Degree Fahrenheit
DFGD	Deep Flue Gas Desulfurization
DOE	US Department of Energy
FGD	Flue Gas Desulfurization
Ft, ft	Feet
GPM, gpm	Gallon per Minute
GPM, gpm	Gallon per Minute
GPS	Gas Pressurized Stripping
H&M	Heat and Material
H_2O	Water
HCl	Hydrogen Chloride
Hg	Mercury
Hg	Mercury
HHV	Higher Heating Value
HP	High Pressure
Hr, hr	Hour
IEP	Innovations for Existing Plants
ILP	Intermediate Low Pressure
kWe	Kilowatt electric
kWh	kilowatt hour
LB/Hr, lb/hr,	Pound Mass Per Hour
LCOE	Levelized Cost of Electricity
LP	Low Pressure
ME	Major Equipment
MEA	Monoethanolamine
MM	million
MWe	Megawatt electric

N_2	Nitrogen
NETL	National Energy Technology Laboratory
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
O&M	Operating and Maintenance
O_2	Oxygen
PC	Pulverized coal
PCC	Post-Combustion Capture
PM	Particulate Matters
ppmv	Parts per Million by Volume
PSFM	Power Sustems Financial Model
psia	Pounds Per Square Inch, absolute
psig	Pounds Per Square Inch, gauge
Sat	Saturated
SC, S/C	Sub-Contract
SCF	Standard Cubic Foot
SCR	Selective Catalytic Reduction
SH	Superheat
SO_2	Sulfur Dioxide
ST	Short Ton
STG	Steam Turbine Generator
TBD	To be determined
TDC	Total Direct Cost
TFC	Total Field Cost
TG	Turbine Generator
TPC	Total Plant Cost
TS&M	Transport, Storage & Monitoring
VOC	Volatile Organic Compound
vol%	Percentage by Volume
WBT	Wet Bulb Temperature
WFGD	Wet Flue Gas Desulfurization
WHR	Waste Heat Recovery