COST AND PERFORMANCE BASELINE FOR FOSSIL ENERGY PLANTS SUPPLEMENT: SENSITIVITY TO CO_2 CAPTURE RATE IN COAL-FIRED POWER PLANTS

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Errata

This report is a re-issue of the 2019 study (published on October 10, 2019), revised as follows:

1) The material and direct labor costs associated with the CO_2 capture system for the supercritical pulverized coal partial capture cases are scaled on a combination of inlet gas volumetric flow rate (40 percent) and captured CO_2 mass flow rate (60 percent) with an exponent of 0.6 whereas the 2019 issue of this study erroneously held these costs constant.
2) The wet flue gas desulfurization (FGD) unit's water demand is satisfied first by internally recycling water discharged from the CO_2 capture process, with the remainder being satisfied by raw water withdrawal. Excess process water, if any, from the CO_2 capture system is discharged. The 2019 issue of this study satisfied the remaining wet FGD water demand by internally recycling water from the cooling tower blowdown.
3) The values reported for the levelized cost of electricity (LCOE) accuracy range for integrated gasification combined cycle (IGCC) cases in Exhibit A-4 were revised from -15%/+30% to -25%/+50%.
4) Exhibits portraying corrected data were updated, with accuracy ranges added to LCOE, breakeven CO_2 sales price, and breakeven CO_2 emissions penalty charts where appropriate.
5) Section 2.1was revised to more clearly reflect the relationship between the steady-state, full-load CO_2 emission rates reflected in this study, and the higher CO_2 emission rates anticipated for a plant under typical operating conditions.

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LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

ASU	Air separation unit
Btu	British thermal unit
CO	Carbon monoxide
CO_2	Carbon dioxide
COS	Carbonyl sulfide
DOE	Department of Energy
EPA	Environmental Protection Agency
ESPA	Energy Sector Planning and Analysis
FD	Forced draft
FG	Flue gas
FGD	Flue gas desulfurization
GEP	General Electric Power
gpm	Gallons per minute
h, hr	Hour
H_2	Hydrogen
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
HCl	Hydrochloric acid
Hg	Mercury
HHV	Higher heating value
HP	High pressure
HRSG	Heat recovery steam generator
ID	Induced draft
IGCC	Integrated gasification combined cycle
IP	Intermediate pressure
kg	Kilogram
KO	Knockout
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
kWt	Kilowatt thermal
lb	Pound
lb/MMBtu	Pounds per million British thermal units
lb/MWh-gross	Pounds per gross megawatt hour
lb/MWh-net	Pounds per net megawatt hour
LCOE	Levelized cost of electricity
LP	Low pressure
LTHR	Low temperature heat recovery
MESA	Mission Execution and Strategic Analysis
MMBtu	Million British thermal units
MW, MWe	Megawatt electric
MWh	Megawatt-hour
N/A	Not available/applicable
N_2	Nitrogen
NaOH	Sodium hydroxide
NETL	National Energy Technology Laboratory
NOAK	n^{th}-of-a-kind
NOx	Nitrogen oxide
PA	Primary air
PC	Pulverized coal
PM	Particulate matter
QGESS	Quality Guidelines for Energy System Studies
SC	Supercritical
SC PC	Supercritical pulverized coal
SCR	Selective catalytic reduction
SDE	Spray dryer evaporator
SO_2	Sulfur dioxide
SOx	Oxides of sulfur
T&S	Transport and storage
TBtu	Trillion British thermal units
tonne	Metric ton (1,000 kg)
TPC	Total plant cost
U.S.	United States
WGS	Water gas shift
ZLD	Zero liquid discharge
°F	Degrees Fahrenheit
$MM	Million dollars

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EXECUTIVE SUMMARY

The cost and performance of various plants designed to meet a range of carbon dioxide (CO_2) emission limits are evaluated in this report by varying the CO_2 capture rate. The base cases for these designs are the supercritical (SC) pulverized coal (PC) plant and the General Electric Power (GEP) integrated gasification combined cycle (IGCC) plant from the Department of Energy (DOE) National Energy Technology Laboratory (NETL) report "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4" ("Bituminous Baseline"). [1]

The SC PC plants developed in this study were based on Bituminous Baseline Case B12B, differing only in the addition of a bypass flow path that allows for an appropriate portion of the flue gas stream exiting the desulfurization system to be directed toward the stack, which reduces the amount of CO_2 captured in the Cansolv process. The IGCC plants developed in this study were based on Case B5B, differing by bypassing the water gas shift reactors, either partially or entirely, and thereby reducing the concentration of CO_2 in the syngas and consequently reducing the amount of CO_2 captured in the Selexol process. The major components of the underlying CO_2 capture technologies in the plants were preserved with minimal modifications to the overall processes. All cases include cost and performance information from vendor quotes (2016 bases).

The results of the study are summarized in Exhibit ES-1 and Exhibit ES-2 for SC PC and IGCC cases, respectively. The exhibits depict the variations of the plant higher heating value (HHV) efficiencies, levelized costs of electricity (LCOEs) excluding transportation and storage (T&S), breakeven CO_2 sales prices (equivalent to the minimum CO_2 plant gate sales price that will incentivize CO_2 capture), and overall CO_2 capture rate with partial capture design CO_2 emission levels.

Exhibit ES-3 provides a tabular listing of salient results, including a comparison of the emissions on a net and gross output basis. The HHV efficiency of the plants expectedly increases with an increase in the allowable CO_2 emission levels, varying from 31.5 and 33.7 percent for the SC PC and IGCC plants with 90 percent CO_2 capture, respectively, to 40.3 and 39.9 percent for the SC PC and IGCC plants with the highest CO_2 emission (no CO_2 capture), respectively.

The plant LCOE (ex. T&S) decreases with an increase in allowable CO_2 emissions primarily due to the lower capital and operating costs for the reduced sizes of the capture systems and the reduced parasitic load of the CO_2 capture equipment. For the SC PC plants, the LCOE (ex. T&S) of the plant featuring 90 percent CO_2 capture is approximately 64 percent higher than the LCOE (ex. T&S) of the plant with no CO_2 capture. For the IGCC plants, the LCOE (ex. T&S) of the plant featuring 90 percent CO_2 capture is approximately 34 percent higher than the LCOE (ex. T&S) of the plant with no CO_2 capture. The capture impact on the IGCC plants is smaller than that of the SC PC plants because the CO_2 is at a higher concentration and pressure in the IGCC syngas than in the SC PC flue gas (a portion of the lower relative impact is due to the higher LCOE (ex. T&S) of the IGCC plant with no CO_2 capture, compared to that of the analogous SC PC plant).

Exhibit ES-1. Variation of LCOE (ex. T&S), HHV net plant efficiency, breakeven CO_2 sales price, and CO_2 capture rate with design emission levels for SC PC cases[a]

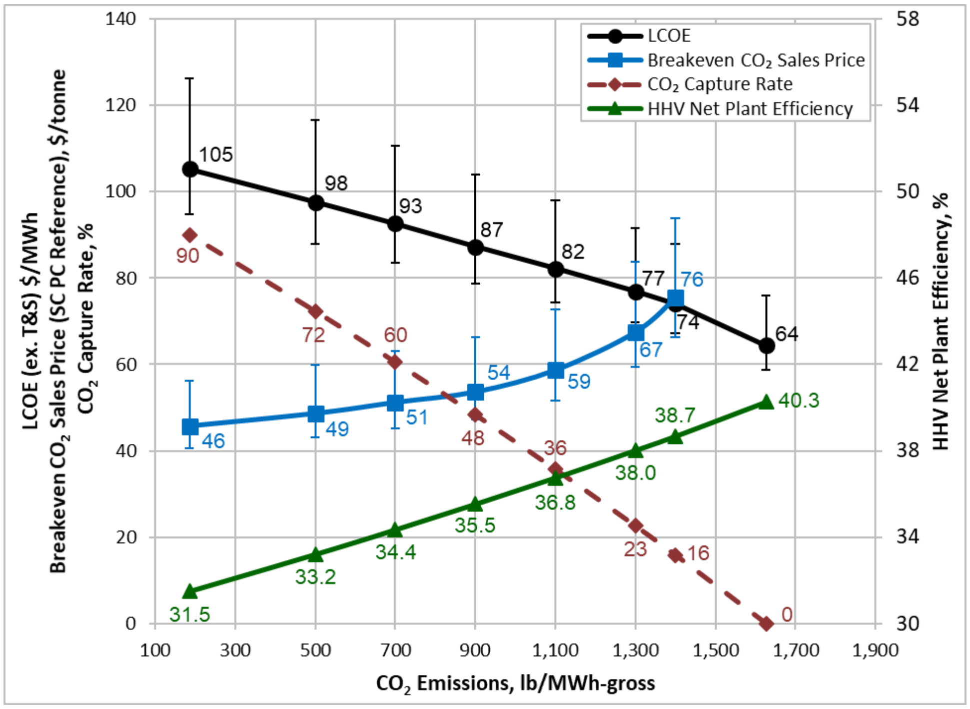
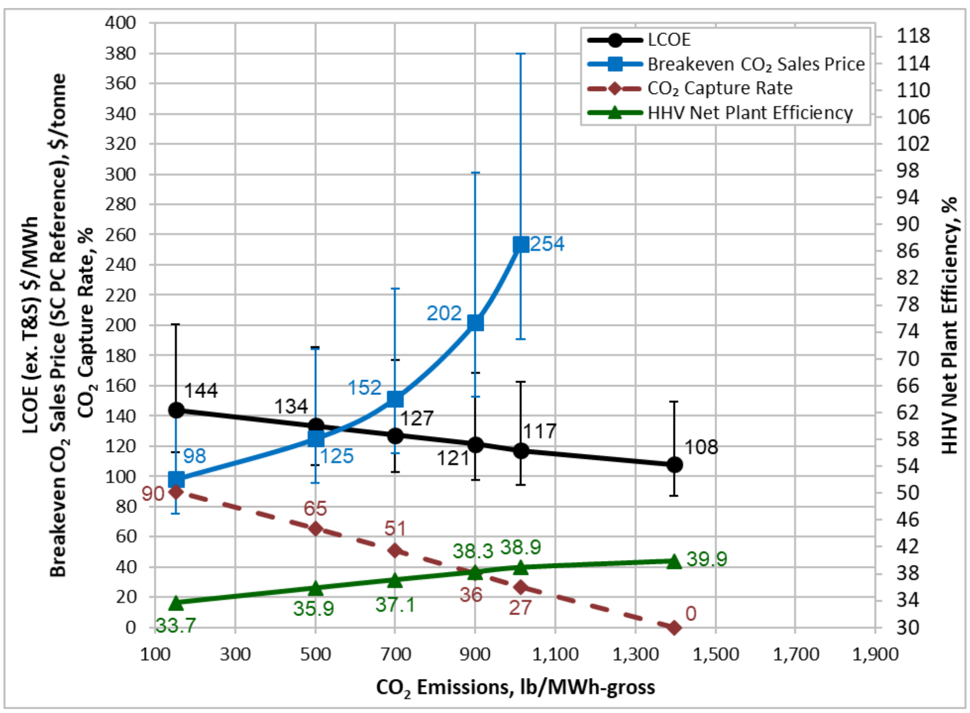


Exhibit ES-2. Variation of LCOE (ex. T&S), HHV net plant efficiency, breakeven CO_2 sales price, and CO_2 capture rate with design emission levels for IGCC cases[a]



[a] As the lowest cost coal case with no CO_2 capture, the SC PC Case B12A serves as the common reference plant for both the SC PC and the IGCC cases.

Exhibit ES-3. Summary of results

Plant Type	CO_2 Emission Level		CO_2 Capture Rate	HHV Efficiency	LCOE (ex. T&S)[A]	Breakeven CO_2 Sales Price[B]	Breakeven CO_2 Emissions Penalty[B, C]
	lb/MWh-gross	lb/MWh-net	%	%	$/MWh	$/tonne CO_2	$/tonne CO_2
SC PC	1,627	1,714	0	40.3	64.4	N/A	N/A
	1,400	1,502	16	38.7	74.1	75.5	113.8
	1,300	1,405	23	38.0	76.9	67.5	102.8
	1,100	1,208	36	36.8	82.2	58.7	90.9
	900	1,004	48	35.5	87.2	53.6	84.1
	700	794	60	34.4	92.6	51.2	80.8
	500	577	72	33.2	97.5	48.7	77.5
	185	219	90	31.5	105.3	45.7	73.5
IGCC	1,396	1,685	0	39.9	107.9	N/A	N/A
	1,014	1,252	27	38.9	117.1	253.8	261.5
	900	1,121	36	38.3	121.3	202.0	222.0
	700	885	51	37.1	127.3	151.7	178.4
	500	644	65	35.9	133.7	125.1	154.1
	151	201	90	33.7	144.2	98.2	128.1

[A]Financing structures are presented in NETL's "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessment of Power Plant Performance" [2]
[B]Both the breakeven CO_2 sales price and emissions penalty were calculated based on the non-capture SC PC Case B12A for all coal cases
[C]The breakeven CO_2 emissions penalty represents the minimum cost of, or penalty on, CO_2 emissions that will incentivize the carbon capture cases.

Average annual CO_2 emissions from operating plants are likely to be higher than the baseload, steady-state design emissions rates shown in Exhibit ES-3 due to start-up, shutdown, part-load operation, and performance degradation through maintenance cycles. Lower design emissions rates to ensure adequate margins may be required for compliance with CO_2 emissions regulations; however, given that the slope of the variation of LCOE (ex. T&S) with CO_2 emission levels is not steep for either SC PC or IGCC plants, designing for this margin does not have major cost implications. See Section 2.1 for further discussion.

The breakeven CO_2 sales price is higher at lower capture rates primarily due to the associated economies of scale. Should such CO_2 revenues be available, then the higher capture rate designs would be a more cost-effective method of CO_2 abatement; however, the lower capture rate designs represent lower incremental costs than the plant with 90 percent capture. Deployment of lower capture rate plants enables demonstration, progressive scaling, and optimization of the CO_2 capture system with lower absolute costs, while facilitating the smooth transition, from both economic and process perspectives, to subsequent plants with higher capture rates.

The observations in this document are made with the caveat that the differences in costs between cases of similar emission levels are less than the absolute accuracy of the capital cost estimates (IGCC: -25 percent/+50 percent, AACE Class 5; PC: -15 percent/+30 percent, AACE Class 4); however, all cases were evaluated using a common set of technical and economic assumptions, which allows for meaningful comparisons among the cases.

Special Considerations on Reported Costs

Capital costs:

The capital cost estimates documented in this report reflect varying uncertainty ranges by technology type (i.e., IGCC: -25 percent/+50 percent, AACE Class 5; PC: -15 percent/+30 percent, AACE Class 4) [2] [3] [4], based on the level of engineering design performed. In all cases, the report intends to represent the next commercial offering, and relies on vendor cost estimates for component technologies. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs (a challenge for emerging technologies).

Costs of mature technologies and designs:

The cost estimates for plant designs that only contain fully mature technologies that have been widely deployed at commercial scale (e.g., PC power plants without CO_2 capture) reflect nth-of-a-kind (NOAK) on the technology commercialization maturity spectrum. The costs of such plants have dropped over time due to "learning by doing" and risk reduction benefits that result from serial deployments as well as from continuing research and development.

Costs of emerging technologies and designs:

The cost estimates for plant designs that include technologies that are not yet fully mature (e.g., IGCC and any plant with CO_2 capture) use the same cost estimating methodology as for the mature plant designs, which does not fully account for the unique cost premiums associated with the initial, complex integrations of emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of the IGCC and capture plants may incur costs higher than those reflected within this report.

Other factors:

Costs for all the real-world projects are expected to deviate from the cost estimates in this report due to project- and site-specific considerations (e.g., contracting strategy, local labor costs and availability, seismic conditions, water quality, financing parameters, local environmental concerns, weather delays) that may make construction more costly. Such variations are not captured by the reported cost uncertainty.

Future cost trends:

Continuing research, development, and demonstration is expected to result in designs that are more advanced than those assessed by this report, leading to costs that are lower than those estimated herein.

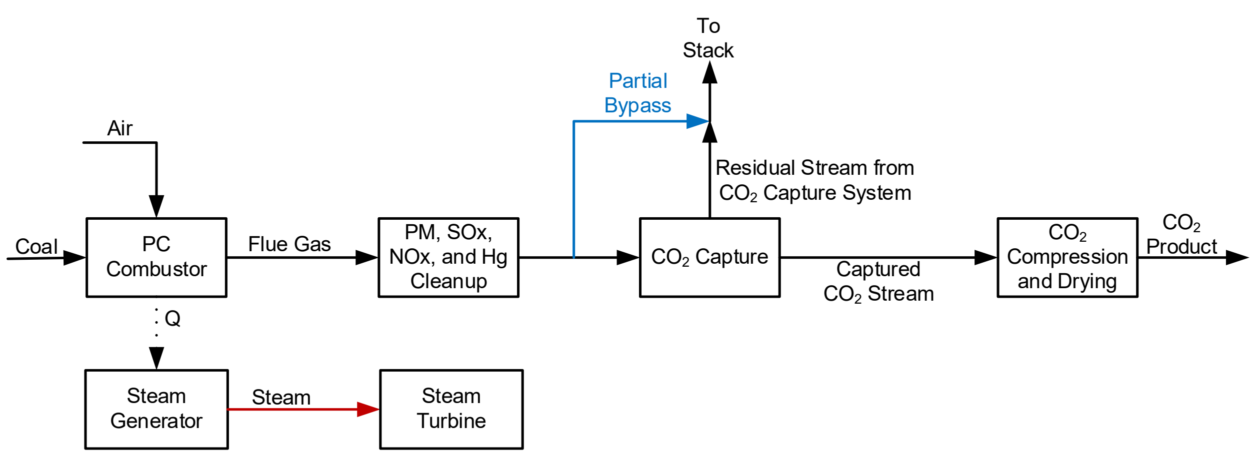
1 INTRODUCTION

The Department of Energy (DOE) National Energy Technology Laboratory (NETL) "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4" study [1], hereafter referred to as the "Bituminous Baseline," has evaluated the performance and cost of fossil fuel-fired plants that are designed without capture of the carbon contained in the inlet fuel, as well as plants with 90 percent CO_2 capture. The cost and performance of coal-based plants that are modified for lower levels of CO_2 capture (partial capture designs) presented in this report are of general interest to NETL insofar that the cost and performance penalties may be mitigated. Specifically, plant designs with lower capture rates have the potential to enable demonstration, progressive scaling, and optimization of the CO_2 capture system with lower absolute costs, while facilitating the smooth transition, from both economic and process perspectives, to subsequent plants with higher capture rates.

The objective of this report is to evaluate the cost and performance of a supercritical (SC) pulverized coal (PC) plant with CO_2 capture (Bituminous Baseline Case B12B) and an integrated gasification combined cycle (IGCC) plant with CO_2 capture (Bituminous Baseline Case B5B), both modified to achieve various levels of partial capture. [1] The partial capture cases presented in this report preserve the major components of the underlying CO_2 capture technology utilized in the corresponding reference plants with minimal modifications to the overall processes.

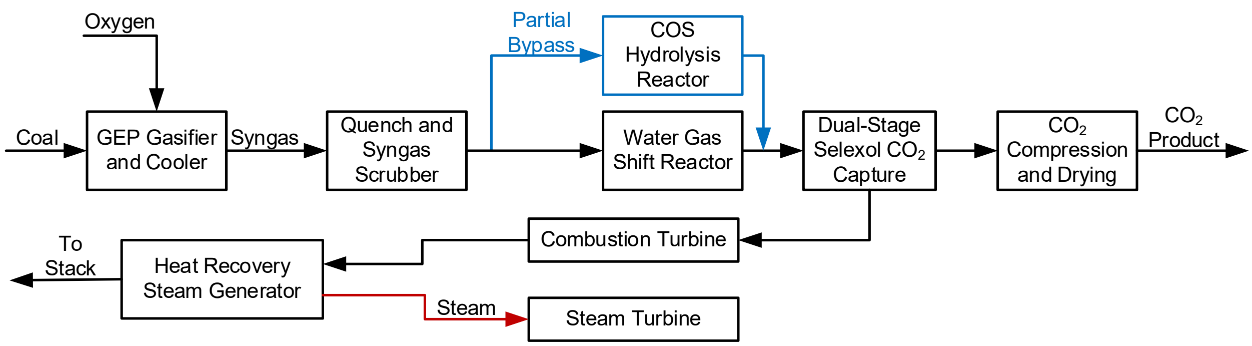
As shown in Exhibit 1-1, an appropriate portion of the flue gas stream exiting the desulfurization system of the SC PC cases is diverted to the stack, bypassing the CO_2 capture system, in order to evaluate systems with CO_2 emissions ranging from approximately 1,627 to 185 lb/MWh-gross (zero to 90 percent CO_2 capture). Consistent with the reference plant (Case B12B), the amine-based Shell Cansolv system—designed to capture 90 percent of the CO_2 in its inlet stream—is employed as the CO_2 capture system.

Exhibit 1-1. Simplified SC PC schematic – modifications for partial capture cases



In the IGCC cases, the reduction in the CO_2 capture requirement also reduces the need to convert much of the carbon monoxide (CO) in the gasifier exit gas into CO_2 via water gas shift (WGS) reactors for eventual capture in the dual-stage Selexol process. Instead, the CO can be retained in the syngas and sent to the gas turbine for combustion and power generation. A simplified block flow diagram of the overall IGCC process is shown in Exhibit 1-2. A WGS bypass line including a carbonyl sulfide (COS) hydrolysis reactor has been added (in blue) to illustrate the process modification for the partial capture cases that is used to evaluate systems with CO_2 emissions ranging from approximately 1,396 to 151 lb/MWh-gross (zero to 90 percent CO_2 capture). The key differences between the cases are reflected in the concentration of CO_2 in the feed to the dual-stage Selexol unit. These values range from approximately 16.3 mole percent for the 27 percent CO_2 capture case to approximately 39.7 mole percent for the 90 percent CO_2 capture case (B5B).

Exhibit 1-2. Bituminous Baseline IGCC schematic – modifications for partial capture cases



2 DESIGN BASIS

The modified plants are assumed to be located at a generic midwestern United States site, operating under ambient International Standards Organization conditions with site and coal characteristics that are identical to the Bituminous Baseline. [1] The emission targets are assumed to be the same as those of the Bituminous Baseline, except for the CO_2 emission limit, which is variable in the present investigation. The plants are evaluated at a rated net power of 650 MWe with an assumed capacity factor of 85 percent.

2.1 DESIGN EMISSION TARGETS

For a plant to achieve a target annual average CO_2 emission level, it must be designed to emit CO_2 at a rate sufficiently lower than the target to account for various factors that potentially result in higher emission levels, such as the frequency of startups and shutdowns, partial load operation, and equipment aging that results in increased net plant heat rate.

Exhibit 2-1 provides a simplified, hypothetical example of design emission levels that a 650 MWe plant operating with an assumed capacity factor of 85 percent could use to achieve an average annual CO_2 emission rate of 1,400 lb-CO_2/MWh[b], only accounting for various frequencies of startups and shutdowns. The values provided in Exhibit 2-1 are intended for illustrative purposes only and are not based on plant data. Additional data are required to accurately estimate startup and shutdown CO_2 emissions for any particular plant.

This example does not account for additional considerations that potentially result in higher emission levels, such as performance degradation caused by aging equipment, operation at part-load (where the unit operates at lower capacity with a lower efficiency than at full load), and off-design conditions (e.g., unplanned process upsets).

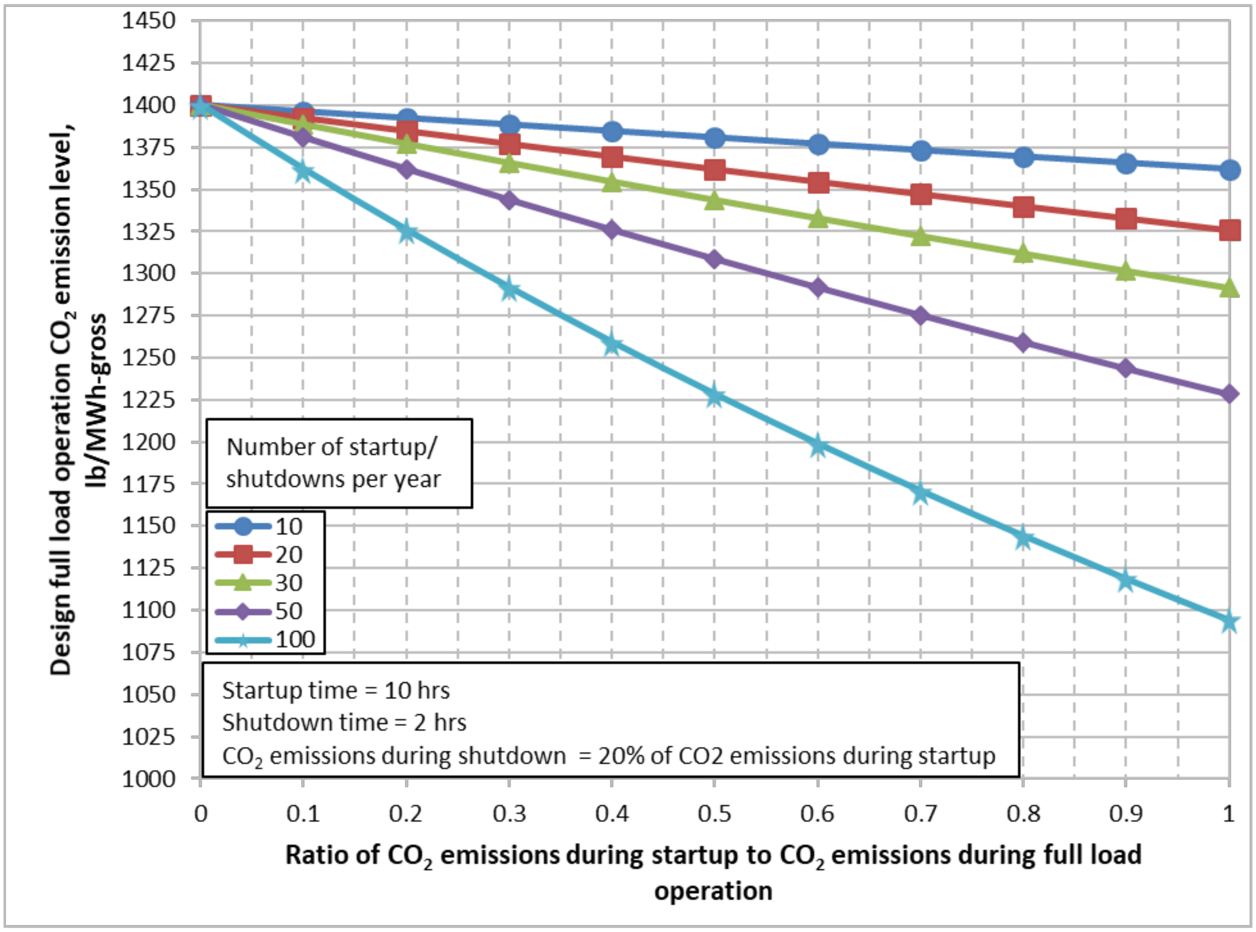
The non-baseload circumstances described above are reflective of normal operations of all fossil-fueled power plants and must be accounted for when evaluating time-averaged CO_2 emissions. The net result of these circumstances is a time averaged capture rate that is greater than the steady-state capture system design specification.

Exhibit 2-1 assumes that no power is generated once the plant enters the startup or shutdown cycle, that the CO_2 emitted during shutdown is equal to 20 percent of the CO_2 emitted during startup, and that the duration of startup and shutdown cycles are 10 hours and 2 hours, respectively.

As an example, and considering the assumptions, basis, and limitations highlighted previously, a hypothetical plant with startup CO_2 emissions equal to full load CO_2 emissions (ratio of 1.0) that incurs 10 startup and shutdown cycles per year could achieve a 12-operating-month average emission rate of 1,400 lb-CO_2/MWh by operating at a higher capture rate (in this example, a full-load design CO_2 emission level below 1,362 lb-CO_2/MWh).

[b] As a point of reference, the CO_2 emission rule states that newly-constructed fossil fuel-fired steam generating units are required to meet a unit-specific emission limit of 1,400 lb-CO_2/MWh on a 12-operating-month average. The required emission limit is inclusive of startup, shutdown, and upset emissions from the permitted source. [5]

Exhibit 2-1. Hypothetical example of design emission levels as a function of startup and shutdown frequencies and emissions



2.2 SC PC Partial Capture Design

The block flow diagram of the modified SC PC system, shown in Exhibit 2-2, differs from that of the reference Case B12B only by the addition of the CO_2 capture system bypass flue gas stream, which can be tuned to meet the desired CO_2 emission level.

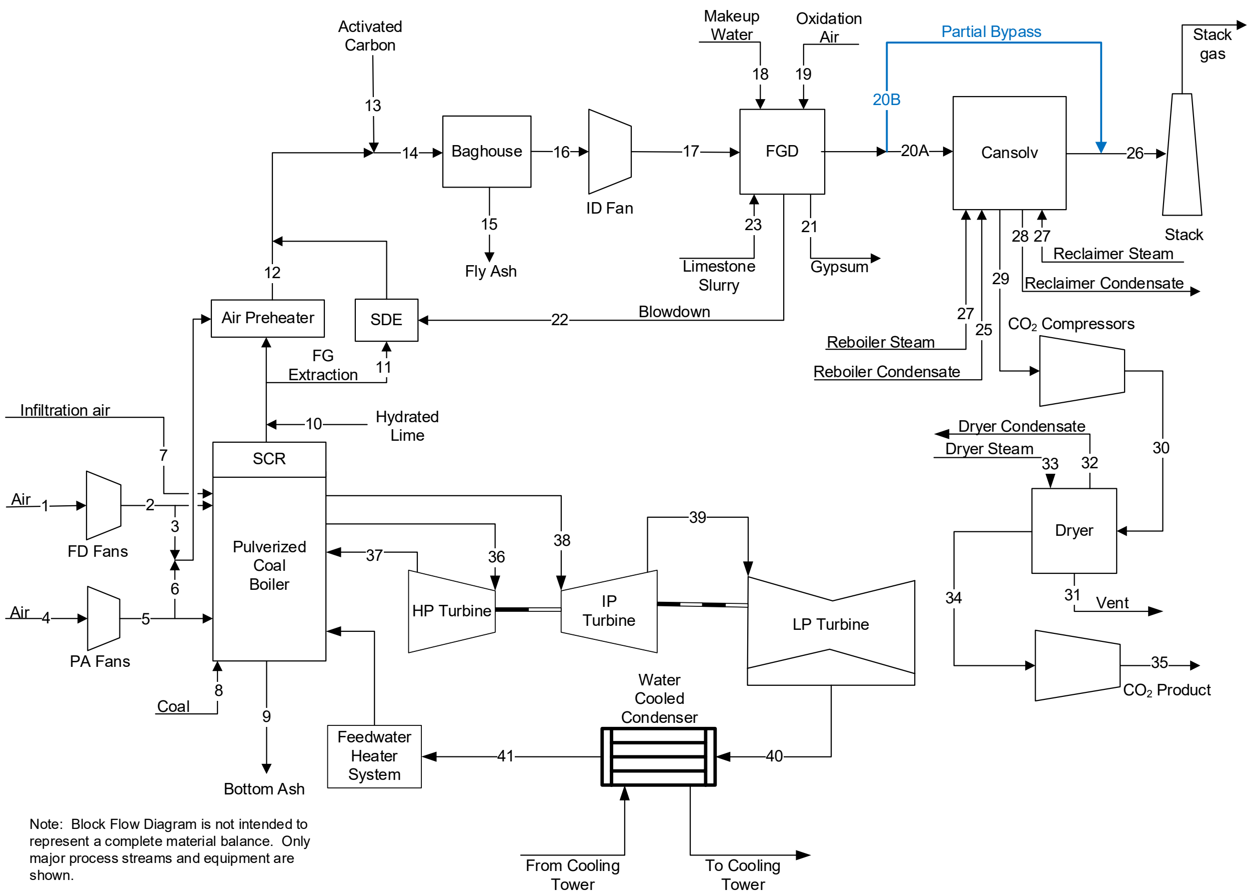
The basis for the cost and performance of all SC PC partial capture cases is the previously mentioned Shell Cansolv solvent-based system operating at 90 percent capture. No performance penalties were assessed due to the operation of the capture system at a scale smaller than the design specified in the referenced vendor data; accordingly, its auxiliary load was computed directly based on the CO_2 product flow rate.

The capital cost of the CO_2 capture system was scaled on a combination of inlet gas volumetric flow rate (40 percent) and captured CO_2 mass flow rate (60 percent), with an exponent of 0.6, in accordance with the Quality Guidelines for Energy System Studies (QGESS) procedures. [6]

It is assumed that a CO_2 monitoring system is included in the standard instrumentation and control accounts of the Bituminous Baseline and that a bypass system is included in the design of the CO_2 capture system in case of failure or emergency shut-down.

While partial bypass of the capture system results in slightly higher SO_2 emissions than in Case B12B, the emission levels will be lower than the values for Case B12A (no CO_2 capture), which is tantamount to a special subset of the modified system where all the flue gas flow bypasses the CO_2 capture system.

Exhibit 2-2. Block flow diagram of the modified B12B process for partial capture

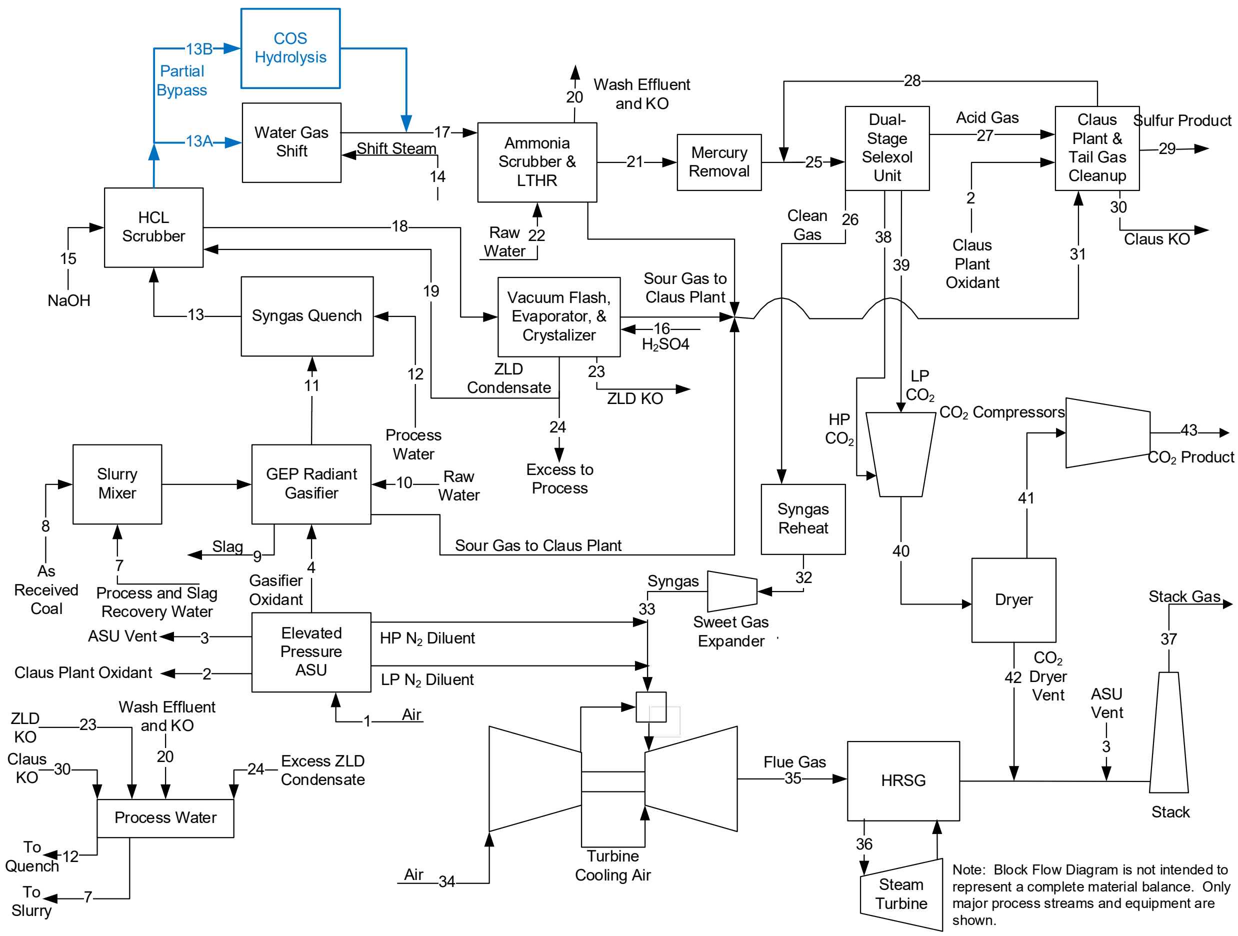


The plants are evaluated at a rated net power of 650 MWe with an assumed capacity factor of 85 percent. All process parameters and cost assumptions are identical to the reference Case B12B.

2.3 IGCC Partial Capture Design

The block flow diagram of the modified IGCC system, shown in Exhibit 2-3, differs from that of the reference Case B5B only by the addition of a bypass around the WGS reactors and the inclusion of a COS hydrolysis reactor in the bypass line. The amount of bypass around the WGS reactors can be tuned to meet the desired CO_2 emission level.

Exhibit 2-3. Block flow diagram of the modified B5B process for partial capture



The plants are evaluated at a variable net power, sized to maintain a constant combustion turbine gross power output of 464 MW, with an assumed capacity factor of 80 percent. All process parameters and cost assumptions are identical to Case B5B.

2.3.1 Water Gas Shift and COS Hydrolysis

The 500 through 900 lb/MWh-gross CO_2 emissions cases were achieved exactly by reducing the amount of syngas sent to the WGS reactors. The 1,000 lb/MWh-gross CO_2 emission case, however, is nominal. The CO_2 emissions from this case are the result of eliminating the WGS reactors and passing the entire gasifier exit stream through the COS hydrolysis reactor instead.

The reduced flow through the WGS reactor also increases the amount of waste heat available for steam generation, resulting in higher gross power output from the steam cycle for the partial capture cases.

The capital costs of the WGS and COS hydrolysis reactors were scaled on their respective estimated catalyst volumes with an exponent of 0.8 in accordance with QGESS procedures. [6]

2.3.2 CO_2 Capture – Dual-Stage Selexol

The basis for the cost and performance of all IGCC partial capture cases is the previously mentioned dual-stage Selexol solvent-based system designed to achieve 90 percent CO_2 removal in the reference Case B5B.

As the varying partial pressure of the syngas constituents impacts the performance of the CO_2 capture system (e.g., rate of absorption), modifications to the design and operation of the CO_2 capture system (e.g., residence time, circulation rates) would be required to maintain desired performance (e.g., high CO_2 removal rate, high CO_2 purity) at the expense of higher auxiliary loads and/or higher capital costs. However, vendor quotes for the cost and performance of the dual-stage Selexol system operating at various partial CO_2 pressures could not be obtained, and no publicly available data could be identified that correlates CO_2 partial pressures to AGR system cost or performance.

The available AGR models were calibrated at a specific design point and were not intended to predict the system performance across various CO_2 partial pressures. Since multiple design and control parameters were available to reduce the CO_2 product impurity concentration, and no data was available to validate the performance of any design changes, the results of any modified models could not be considered accurate or reflective of commercial capabilities. Therefore, the cost and performance of the CO_2 capture system was maintained consistent with the reference Case B5B.

As the portion of CO_2 removed from the syngas by the CO_2 capture system (94 percent) was assumed constant, partial capture was achieved in the IGCC cases by reducing the concentration of the CO_2 in the syngas entering the CO_2 capture system by reducing the extent of CO shifted to CO_2 by the WGS reactor. As the CO_2 concentration decreases, the CO and H_2 concentrations increase and, due to the assumed constant removal rates, the amount of CO and H_2 removed with the CO_2 product increases, negatively impacting the plant efficiency.

While the CO_2 purity reduced from 99 percent in the reference Case B5B to 95 percent in the case with no WGS reactor (highest CO_2 emissions with a dual-stage Selexol system), no CO_2 purification system was included in this study, as it was assumed that there would be multiple parameters available to adjust and maintain a high purity CO_2 product in a CO_2 capture system designed for partial capture (e.g., CO_2 flash regeneration pressures).

The capital cost of the CO_2 capture system was scaled on a combination of inlet gas volumetric flow rate (82 percent) and captured CO_2 mass flow rate (18 percent), with an exponent of 0.79, in accordance with the Quality Guidelines for Energy System Studies procedures. [6] The distribution across scaling parameters assumed that the H_2S absorption and regeneration equipment would be unaffected by the CO_2 concentration beyond gas volume and that the CO_2 absorption and regeneration equipment would be affected by both the gas volume and CO_2 production rate.

2.4 Partial Capture Calculation

The rate of CO_2 captured is estimated by using the model data and the following equation for each case:

$$CO_2\ Capture\ Rate, \% = \frac{CO_2\ Captured, lb/hr}{CO_2\ Captured, lb/hr + CO_2\ Emitted, lb/hr}$$

2.5 Capture Energy Penalty Calculation

The energy penalty for adding CO_2 capture was estimated using the following equation:

$$CEP = \frac{\left(\frac{1}{HR_{NC}} - \frac{1}{HR_C}\right) * TI_C}{CO_2\ Captured}$$

Where:

CEP = The capture energy penalty, kWh/lb-CO_2

HR_{NC} = The HHV net plant heat rate of the reference plant with no CO_2 capture, Btu/kWh

HR_C = The HHV net plant heat rate of the design plant with CO_2 capture, Btu/kWh

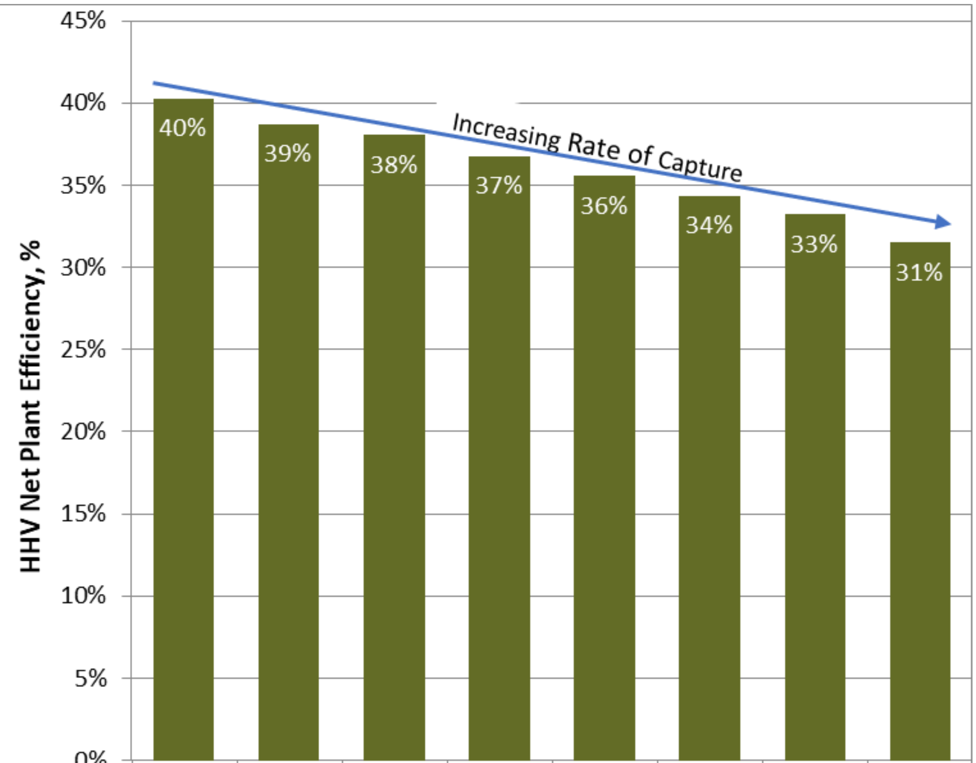
TI_c = The thermal input of coal on an HHV basis, Btu/hr

CO_2 captured = The flow rate of CO_2 captured at the design plant, lb/hr

3 Results and Discussion

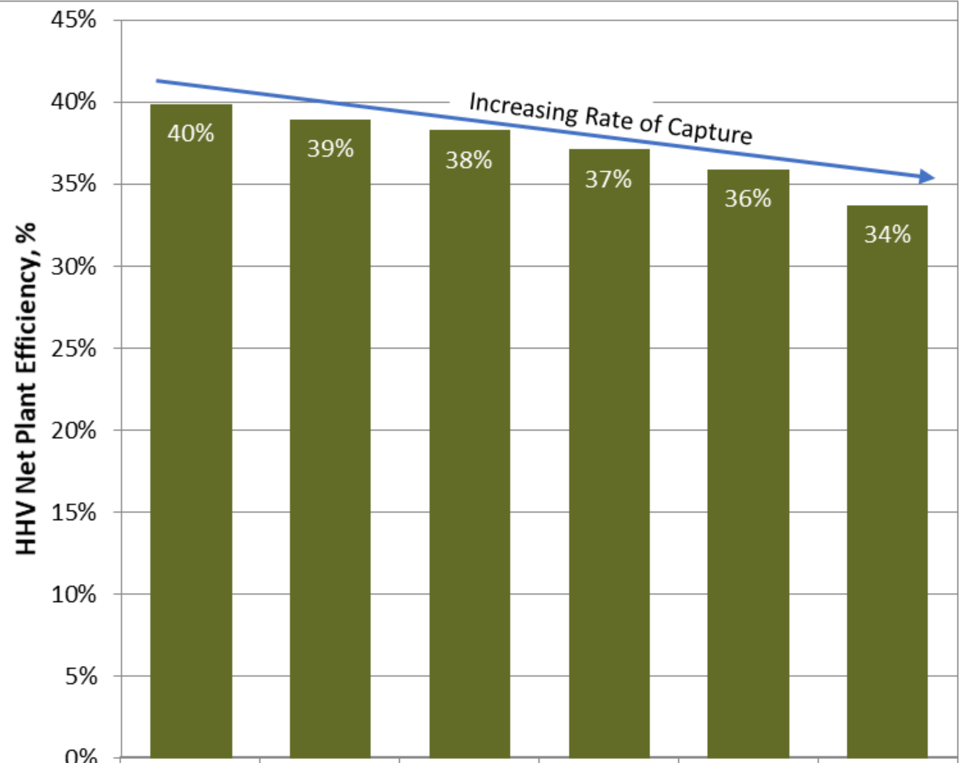
The performance and costs of both the SC PC and IGCC plants were evaluated for various partial capture cases. The higher heating value (HHV) efficiency of the plants expectedly decreases with an increase in the rate of CO_2 capture and corresponding decrease in the allowable CO_2 emission levels. This is illustrated in Exhibit 3-1 for the SC PC cases and in Exhibit 3-2 for the IGCC cases. Additional performance and cost data are found in the Appendix: Key Performance and Cost Summary Tables.

Exhibit 3-1. HHV net plant efficiency for an SC PC plant at various levels of CO_2 capture



	B12A	B12-1400	B12-1300	B12-1100	B12-900	B12-700	B12-500	B12B
CO_2 Emission rate, lb/MWh-gross	1,627	1,400	1,300	1,100	900	700	500	185
CO_2 Emission rate, lb/MWh-net	1,714	1,502	1,405	1,208	1,004	794	577	219
CO_2 Capture Rate	0	16%	23%	36%	48%	60%	72%	90%

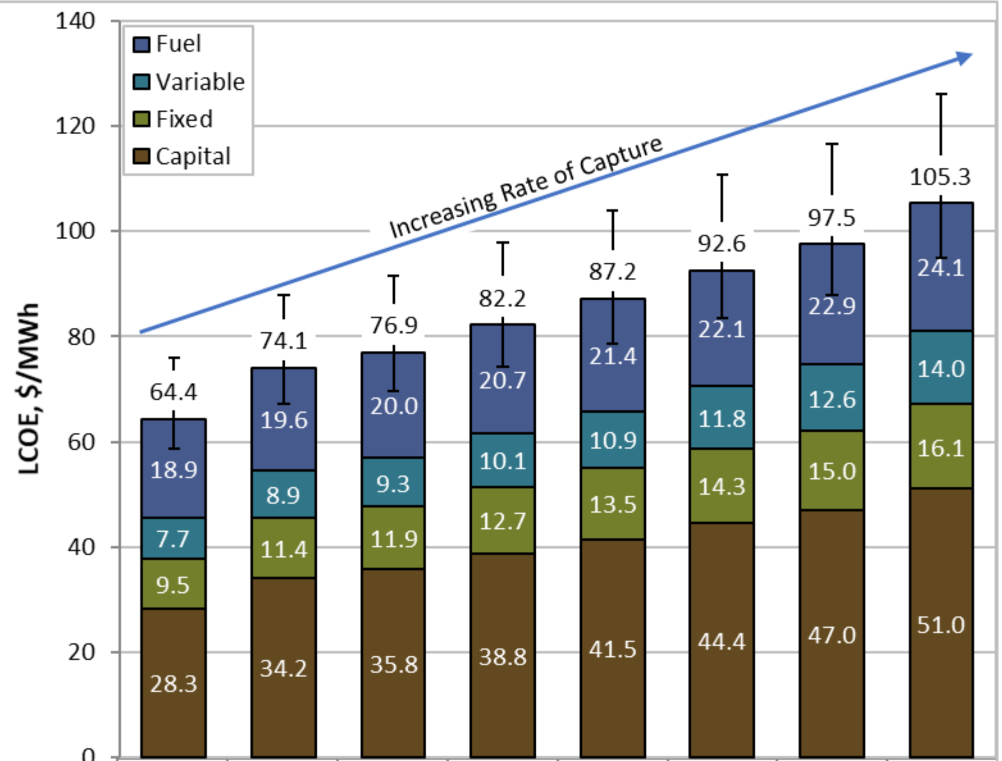
Exhibit 3-2. HHV net plant efficiency for a GEP radiant IGCC plant at various levels of CO_2 capture



	B5A	B5-1000	B5-900	B5-700	B5-500	B5B
CO_2 Emission rate, lb/MWh-gross	1,396	1,014	900	700	500	151
CO_2 Emission rate, lb/MWh-net	1,685	1,252	1,121	885	644	201
CO_2 Capture Rate	0%	27%	36%	51%	65%	90%

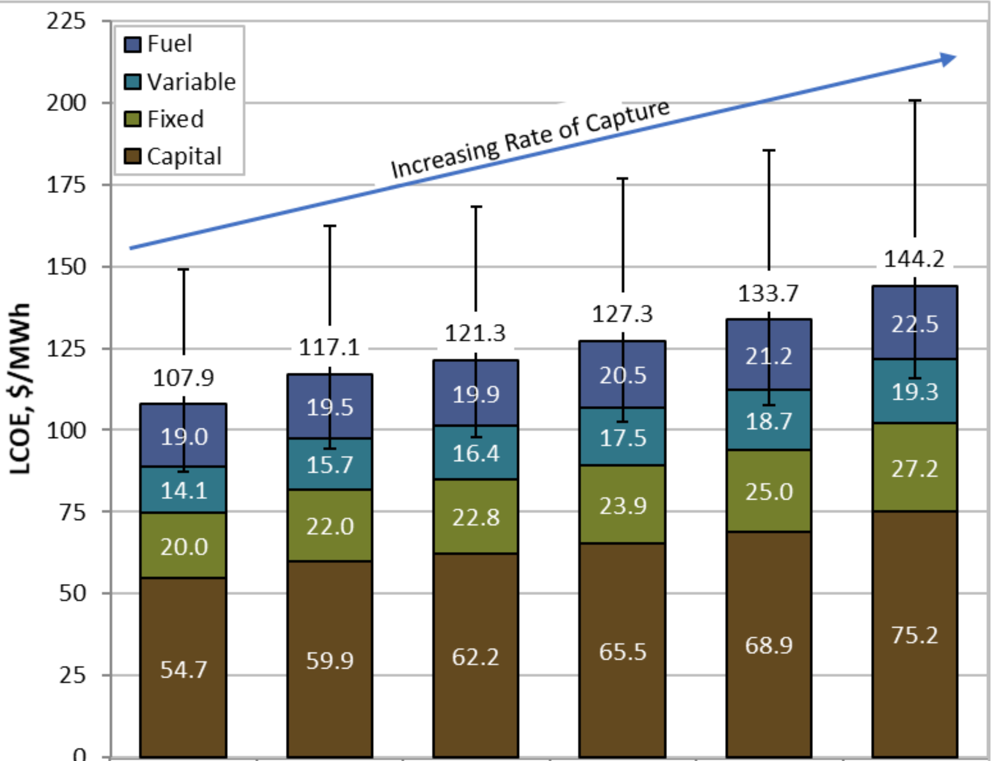
The variations of the levelized cost of electricity (LCOE), excluding transportation and storage (T&S), for different design values of CO_2 emissions are shown in Exhibit 3-3 and Exhibit 3-4, showing that the LCOE (ex. T&S) increases as the capture rate increases.

Exhibit 3-3. LCOE (ex. T&S) for an SC PC plant at various levels of CO_2 capture



	B12A	B12-1400	B12-1300	B12-1100	B12-900	B12-700	B12-500	B12B
CO_2 Emissions, lb/MWh-gross	1,627	1,400	1,300	1,100	900	700	500	185
CO_2 Emissions, lb/MWh-net	1,714	1,502	1,406	1,208	1,004	794	577	219
CO_2 Capture Rate, %	0	16	23	36	48	60	72	90

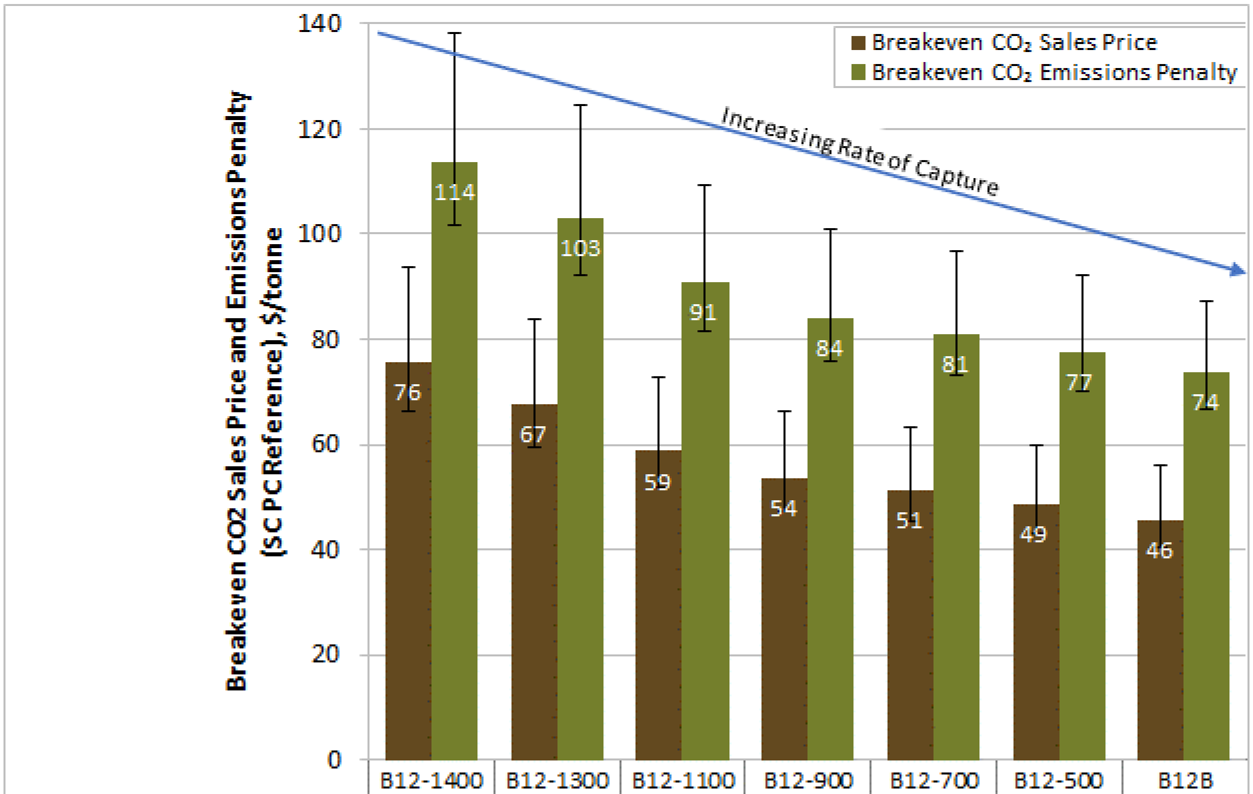
Exhibit 3-4. LCOE (ex. T&S) for a GEP radiant IGCC plant at various levels of CO_2 capture



	B5A	B5-1000	B5-900	B5-700	B5-500	B5B
CO_2 Emissions, lb/MWh-gross	1,396	1,014	900	700	500	151
CO_2 Emissions, lb/MWh-net	1,685	1,252	1,121	885	644	201
CO_2 Capture Rate, %	0	27	36	51	65	90

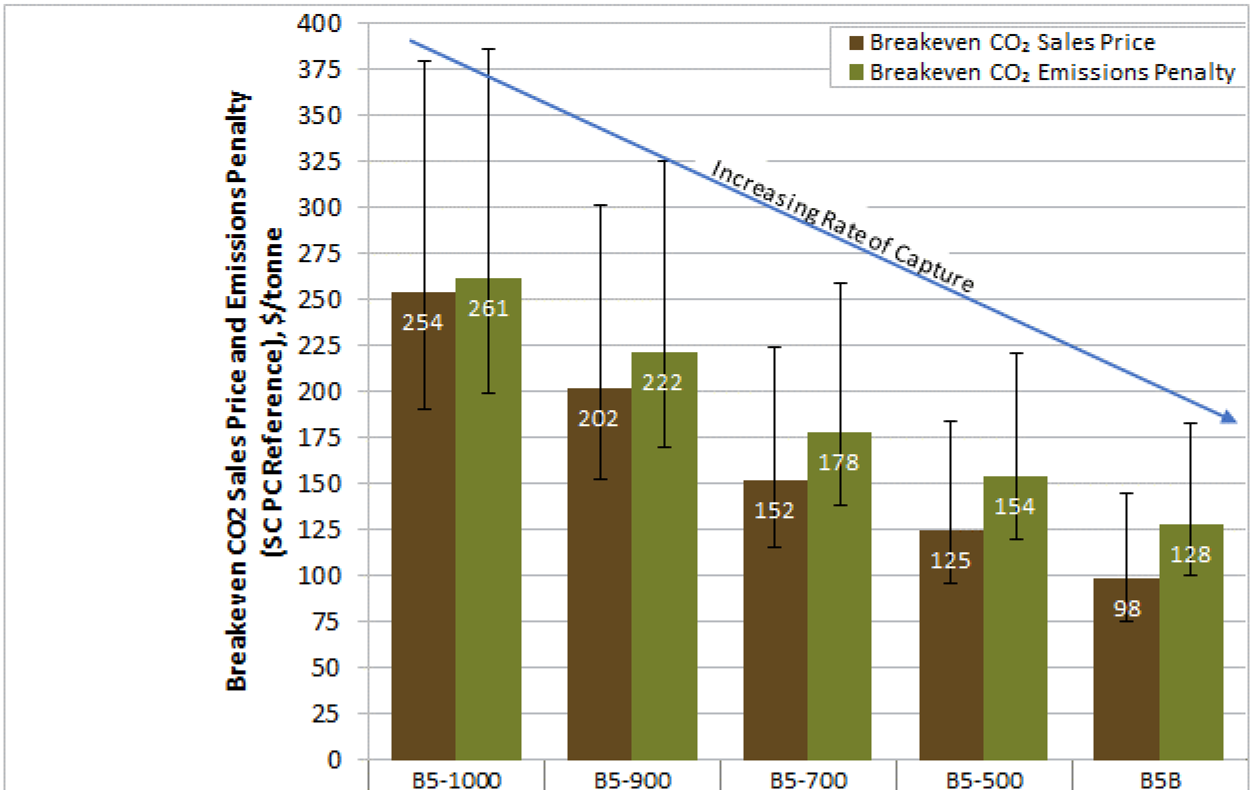
The breakeven CO_2 sales price and emissions penalty are shown in Exhibit 3-5 and Exhibit 3-6. The breakeven CO_2 sales price represents the minimum CO_2 plant gate sales price that will incentivize carbon capture. Similarly, the breakeven CO_2 emissions penalty represents the minimum cost of, or penalty on, CO_2 emissions that will incentivize the carbon capture cases. In lieu of a defined reference plant with no CO_2 capture and as the lowest cost coal case with no CO_2 capture, the SC PC Case B12A serves as the reference plant for both the SC PC and the IGCC cases. As the figures indicate, the breakeven CO_2 sales price and emissions penalty decrease significantly as the capture rate increases due to the economies of scale and the increasing amount of CO_2 captured.

Exhibit 3-5. Breakeven CO_2 sales price and emissions penalty for an SC PC plant at various levels of CO_2 capture



	B12-1400	B12-1300	B12-1100	B12-900	B12-700	B12-500	B12B
CO_2 Emissions, lb/MWh-gross	1,400	1,300	1,100	900	700	500	185
CO_2 Emissions, lb/MWh-net	1,502	1,406	1,208	1,004	794	577	219
CO_2 Capture Rate, %	16	23	36	48	60	72	90

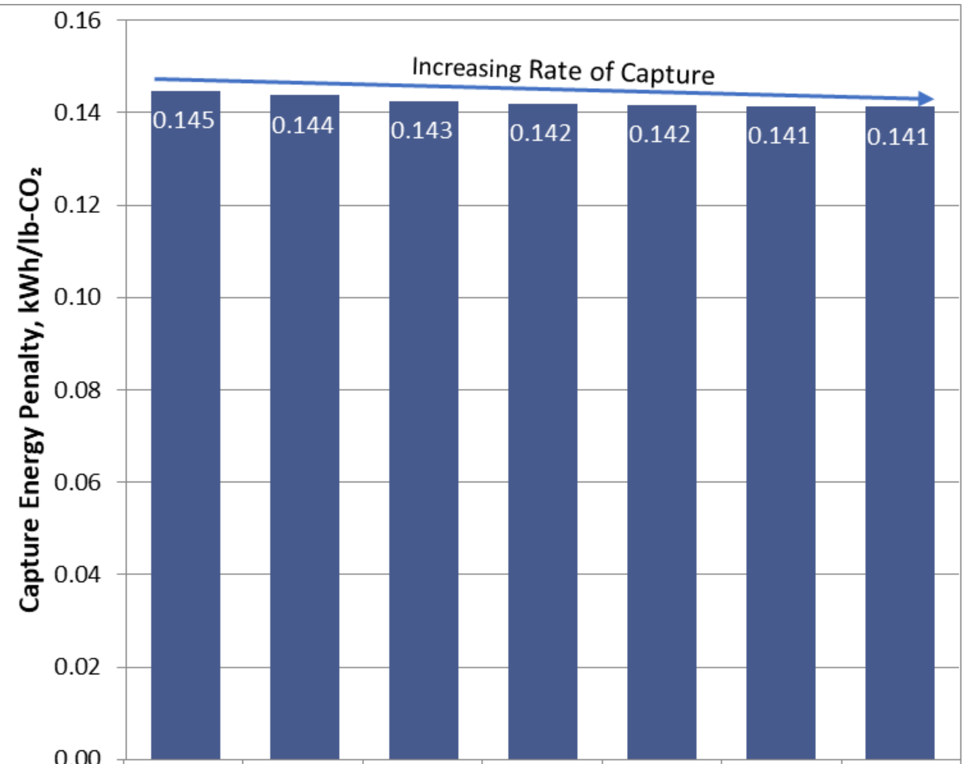
Exhibit 3-6. Breakeven CO_2 sales price and emissions penalty for a GEP radiant IGCC plant at various levels of CO_2 capture



	B5-1000	B5-900	B5-700	B5-500	B5B
CO_2 Emissions, lb/MWh-gross	1,014	900	700	500	151
CO_2 Emissions, lb/MWh-net	1,252	1,121	885	644	201
CO_2 Capture Rate, %	27	36	51	65	90

Due to the use of the bypass around the CO_2 capture system, the capture energy penalties for the SC PC capture cases are nearly constant with a value of approximately 0.14 kWh/lb-CO_2, as shown in Exhibit 3-7. All cases consider 90 percent capture of CO_2 from the flue gas sent to the CO_2 capture system; flue gas that bypasses the CO_2 capture system is unabated.

Exhibit 3-7. Capture energy penalty (kWh/lb-CO_2) for an SC PC plant at various levels of CO_2 capture

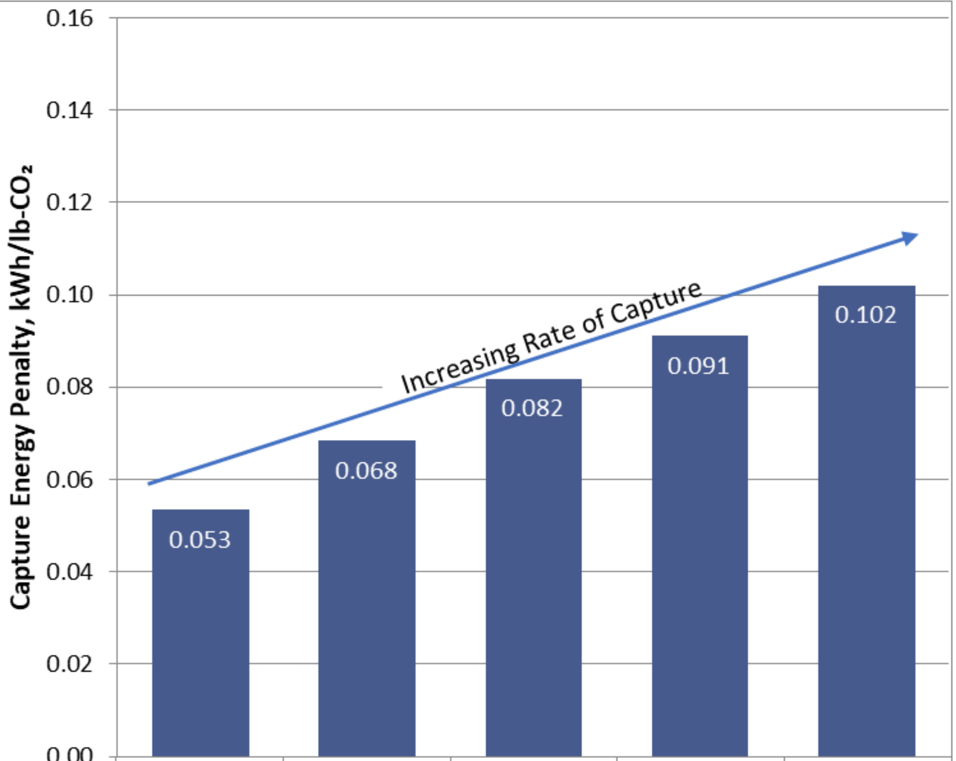


	B12-1400	B12-1300	B12-1100	B12-900	B12-700	B12-500	B12B
CO_2 Emission rate, lb/MWh-gross	1,400	1,300	1,100	900	700	500	185
CO_2 Emission rate, lb/MWh-net	1,502	1,405	1,208	1,004	794	577	219
CO_2 Capture Rate	16%	23%	36%	48%	60%	72%	90%

Due to the addition of water gas shift (WGS) and the intensification of unit operations to drive the CO-conversion reaction to completion, the capture energy penalties for the IGCC capture cases in this study increase significantly with increasing capture rates, as shown in Exhibit 3-8.

Case B5-1000 does not have WGS, sending all the syngas to the COS hydrolysis reactor. Cases B5-900 through B5-500 incrementally increase the amount of syngas sent to the WGS reactor and Case B5B has no COS hydrolysis reactor, sending all the syngas to the WGS reactor. As the amount of syngas sent to the WGS reactor increases, the capture energy penalty increases.

Exhibit 3-8. Capture energy penalty (kWh/lb-CO_2) for a GEP radiant IGCC plant at various levels of CO_2 capture



	B5-1000	B5-900	B5-700	B5-500	B5B
CO_2 Emission rate, lb/MWh-gross	1,014	900	700	500	151
CO_2 Emission rate, lb/MWh-net	1,252	1,121	885	644	201
CO_2 Capture Rate	27%	36%	51%	65%	90%

4 CONCLUSION

Plants that meet a range of design CO_2 emission levels were developed by modifying the Bituminous Baseline cases. For both the SC PC and IGCC plants, lower levels of CO_2 capture result in a lower LCOE, primarily due to the lower capital and operating costs for the reduced sizes of the capture systems and the reduced parasitic loads of the CO_2 capture equipment. In the SC PC cases, the reduction in CO_2 capture system size is due to bypassing a portion of the flue gas to the stack. In the IGCC cases, the reduction in CO_2 capture equipment size is the result of the inlet stream to the CO_2 capture system's mass flow rate and CO_2 concentration decreasing and gas density increasing as the amount of syngas sent to the WGS reactor decreases.

The breakeven CO_2 sales price, equivalent to the minimum plant gate CO_2 sales price (revenue) required to incentivize CO_2 capture relative to an SC PC plant with no CO_2 capture, is higher at lower capture rates primarily due to the associated economies of scale. Should such CO_2 revenues be available, then the higher capture rate designs are a more cost-effective method of CO_2 abatement; however, the lower capture rate designs represent lower incremental costs than the plant with 90 percent capture. Deployment of lower capture rate plants enables demonstration, progressive scaling, and optimization of the CO_2 capture system with lower absolute costs while facilitating the smooth transition, from both economic and process perspectives, to subsequent plants with higher capture rates.

5 References

[1] National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants: Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4," U.S. Department of Energy, Pittsburgh, 2019.

[2] National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," U.S. Department of Energy, Pittsburgh, 2019.

[3] AACE International, Conducting Technical and Economic Evaluations – As Applied for the Process and Utility Industries; TCM Framework: 3.2 – Asset Planning, 3.3 Investment Decision Making, AACE International, 2003.

[4] AACE International, Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries; TCM Framework 7.3 – Cost Estimating and Budgeting, AACE International, 2005.

[5] Environmental Protection Agency, "Standards of Performance for Greenhouse gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units (40 CFR Parts 60, 70, 71)," Environmental Protection Agency, Washington, 2015.

[6] National Energy Technology Laboratory, Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology, Pittsburgh: U.S. Department of Energy, October 2019.

[7] Environmental Protection Agency, "EPA Proposes 111(b) Revisions to Advance Clean Energy Technology," [Online]. Available: https://www.epa.gov/newsreleases/epa-proposes-111b-revisions-advance-clean-energy-technology. [Accessed 2 October 2019].

APPENDIX: KEY PERFORMANCE AND COST SUMMARY TABLES

Exhibit A-1. Estimated performance results for SC PC cases

	Reference Non-Capture Design	Partial Capture Cases						Reference CO_2 Capture Design
Case	**B12A**	**B12-1400**	**B12-1300**	**B12-1100**	**B12-900**	**B12-700**	**B12-500**	**B12B**
CO_2 Capture Rate, %	0	16	23	36	48	60	72	90
Capacity Factor, %	85	85	85	85	85	85	85	85
Gross Power Output, MWe	685	697	703	714	726	737	750	770
Auxiliary Power Requirement, MWe	35	47	53	64	76	87	100	120
Net Power Output, MWe	650	650	650	650	650	650	650	650
Coal Flow rate, lb/hr	472,037	491,184	499,865	517,143	535,034	552,980	572,479	603,246
HHV Thermal Input, kWt	1,613,879	1,679,342	1,709,024	1,768,094	1,829,263	1,890,621	1,957,286	2,062,478
Net Plant HHV Efficiency, %	40.3	38.7	38.0	36.8	35.5	34.4	33.2	31.5
Net Plant HHV Heat Rate, Btu/kWh	8,473	8,820	8,972	9,282	9,601	9,932	10,273	10,834
Raw Water Withdrawal, gpm	6,054	6,113	6,402	6,987	7,592	8,208	8,860	9,911
Process Water Discharge, gpm	1,242	978	1,123	1,417	1,722	2,035	2,361	2,893
Raw Water Consumption, gpm	4,811	5,135	5,279	5,569	5,870	6,174	6,498	7,018
CO_2 Emissions, lb/MMBtu	202	170	157	130	105	80	56	20
CO_2 Emissions, lb/MWhgross	1,627	1,400	1,300	1,100	900	700	500	185
CO_2 Emissions, lb/MWhnet	1,714	1,502	1,405	1,208	1,004	794	577	219
CO_2 Emissions, tonne/yr	3,763,000	3,295,065	3,085,288	2,652,328	2,205,493	1,742,199	1,266,308	480,897
SO_2 Emissions, lb/MMBtu	0.081	0.066	0.060	0.049	0.037	0.026	0.016	0.000
SO_2 Emissions, lb/MWhgross	0.648	0.546	0.501	0.411	0.321	0.232	0.142	0.000
SO_2 Emissions, tonne/yr	1,500	1,286	1,190	992	788	576	359	0
NOx Emissions, lb/MMBtu	0.087	0.085	0.084	0.083	0.081	0.080	0.079	0.077
NOx Emissions, lb/MWhgross	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700
NOx Emissions, tonne/yr	1,619	1,648	1,661	1,688	1,715	1,742	1,773	1,819
PM Emissions, lb/MMBtu	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010
PM Emissions, lb/MWhgross	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090
PM Emissions, tonne/yr	208	212	214	217	221	224	228	234
Hg Emissions, lb/TBtu	0.373	0.365	0.362	0.355	0.349	0.343	0.337	0.328
Hg Emissions, lb/MWhgross	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06
Hg Emissions, tonne/yr	0.007	0.007	0.007	0.007	0.007	0.007	0.008	0.008

Exhibit A-2. Estimated cost results for SC PC cases

	Reference Non-Capture Design	Partial Capture Cases						Reference CO_2 Capture Design
Case	**B12A**	**B12-1400**	**B12-1300**	**B12-1100**	**B12-900**	**B12-700**	**B12-500**	**B12B**
CO_2 Capture Rate	0	16	23	36	48	60	72	90
Total Plant Cost, $/kW	2,099	2,538	2,661	2,882	3,085	3,307	3,500	3,800
Bare Erected Cost	1,548	1,834	1,915	2,062	2,197	2,347	2,476	2,677
Home Office Expenses	271	321	335	361	385	411	433	469
Project Contingency	280	345	364	396	426	459	487	531
Process Contingency	0	38	47	63	78	91	104	123
Total Overnight Cost, $MM	1,678	2,024	2,122	2,297	2,459	2,632	2,788	3,023
Total Overnight Cost, $/kW	2,582	3,116	3,265	3,535	3,782	4,052	4,288	4,654
Owner's Costs	484	578	605	653	697	745	788	854
Total As-Spent Capital, $/kW	2,981	3,597	3,770	4,081	4,366	4,678	4,950	5,372
LCOE (excluding T&S), $/MWh	64.4	74.1	76.9	82.2	87.2	92.6	97.5	105.3
Capital Costs	28.3	34.2	35.8	38.8	41.5	44.4	47.0	51.0
Fixed Costs	9.5	11.4	11.9	12.7	13.5	14.3	15.0	16.1
Variable Costs	7.7	8.9	9.3	10.1	10.9	11.8	12.6	14.0
Fuel Costs	18.9	19.6	20.0	20.7	21.4	22.1	22.9	24.1
LCOE (including T&S), $/MWh	64.4	75.4	78.8	85.3	91.5	98.1	104.4	114.3
CO_2 T&S Costs	0.0	1.3	1.9	3.0	4.3	5.5	6.8	8.9
LCOE (excluding T&S) -15% TPC, $/MWh[1]	58.6	67.1	69.7	74.3	78.8	83.6	88.0	94.9
LCOE (excluding T&S) +30% TPC, $/MWh[1]	75.9	87.9	91.5	98.0	104.1	110.7	116.7	126.2
Breakeven CO_2 Sales Price, $/tonne	N/A	76	67	59	54	51	49	46
Breakeven CO_2 Sales Price -15% TPC, $/tonne[1]	N/A	66	59	52	47	45	43	41
Breakeven CO_2 Sales Price +30% TPC, $/tonne[1]	N/A	94	84	73	66	63	60	56
Breakeven CO_2 Emissions Penalty, $/tonne	N/A	114	103	91	84	81	77	74
Breakeven CO_2 Emissions Penalty -15% TPC, $/tonne[1]	N/A	102	92	82	76	73	70	67
Breakeven CO_2 Emissions Penalty +30% TPC, $/tonne[1]	N/A	138	124	109	101	97	92	87

[1]The accuracy range is applied at the TPC level, which has a consequent impact on the fixed and variable O&M costs. [6]

Exhibit A-3. Estimated performance results for IGCC cases

	Reference Non-Capture Design	Partial Capture Cases				Reference CO_2 Capture Design
Case	**B5A**	**B5-1000**	**B5-900**	**B5-700**	**B5-500**	**B5B**
CO_2 Capture Rate, %	0	27	36	51	65	90
Capacity Factor, %	80	80	80	80	80	80
Gross Power Output, MWe	765	761	758	756	752	741
Auxiliary Power Requirement, MWe	131	145	150	158	168	185
Net Power Output, MWe	634	616	609	597	584	556
Coal Flow rate, lb/hr	464,732	462,396	465,215	470,863	476,084	482,580
HHV Thermal Input, kWt	1,588,902	1,580,918	1,590,555	1,609,865	1,627,716	1,649,926
Net Plant HHV Efficiency, %	39.9	38.9	38.3	37.1	35.9	33.7
Net Plant HHV Heat Rate, Btu/kWh	8,554	8,763	8,917	9,194	9,505	10,118
Raw Water Withdrawal, gpm	4,799	4,768	4,873	5,070	5,241	5,512
Process Water Discharge, gpm	1,033	1,025	1,037	1,061	1,085	5,512
Raw Water Consumption, gpm	3,766	3,743	3,836	4,009	4,156	4,389
CO_2 Emissions, lb/MMBtu	197	143	126	96	68	20
CO_2 Emissions, lb/MWhgross	1,396	1,014	900	700	500	151
CO_2 Emissions, lb/MWhnet	1,685	1,252	1,121	885	644	201
CO_2 Emissions, tonne/yr	3,395,061	2,450,486	2,169,721	1,681,701	1,195,306	355,046
SO_2 Emissions, lb/MMBtu	0.002	0.000	0.000	0.000	0.000	0.000
SO_2 Emissions, lb/MWhgross	0.015	0.000	0.000	0.000	0.000	0.000
SO_2 Emissions, tonne/yr	37	0	0	0	0	0
NOx Emissions, lb/MMBtu	0.054	0.054	0.053	0.051	0.050	0.048
NOx Emissions, lb/MWhgross	0.379	0.382	0.378	0.371	0.366	0.364
NOx Emissions, tonne/yr	922	924	912	892	875	858
PM Emissions, lb/MMBtu	0.007	0.007	0.007	0.007	0.007	0.007
PM Emissions, lb/MWhgross	0.050	0.050	0.051	0.052	0.052	0.054
PM Emissions, tonne/yr	122	122	122	124	125	127
Hg Emissions, lb/TBtu	0.423	0.423	0.419	0.413	0.406	0.395
Hg Emissions, lb/MWhgross	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06	3.00E-06
Hg Emissions, tonne/yr	0.007	0.007	0.007	0.007	0.007	0.007

Exhibit A-4. Estimated cost results for IGCC cases

	Reference Non-Capture Design	Partial Capture Cases				Reference CO_2 Capture Design
Case	B5A	B5-1000	B5-900	B5-700	B5-500	B5B
CO_2 Capture Rate	0	27	36	51	65	90
Total Plant Cost, $/kW	3,822	4,196	4,355	4,576	4,807	5,240
Bare Erected Cost	2,679	2,912	3,021	3,174	3,333	3,631
Home Office Expenses	402	437	453	476	500	545
Project Contingency	557	619	644	679	715	783
Process Contingency	184	228	237	247	258	281
Total Overnight Cost, $MM	2,972	3,165	3,250	3,356	3,452	3,589
Total Overnight Cost, $/kW	4,690	5,142	5,340	5,618	5,908	6,450
Owner's Costs	868	946	985	1,042	1,102	1,210
Total As-Spent Capital, $/kW	5,414	5,936	6,164	6,485	6,821	7,446
LCOE (excluding T&S), $/MWh	107.9	117.1	121.3	127.3	133.7	144.2
Capital Costs	54.7	59.9	62.2	65.5	68.9	75.2
Fixed Costs	20.0	22.0	22.8	23.9	25.0	27.2
Variable Costs	14.1	15.7	16.4	17.5	18.7	19.3
Fuel Costs	19.0	19.5	19.9	20.5	21.2	22.5
LCOE (including T&S), $/MWh	107.9	119.2	124.1	131.5	139.2	152.3
CO_2 T&S Costs	0.0	2.1	2.8	4.1	5.5	8.1
LCOE (excluding T&S) -25% TPC, $/MWh[1]	87.2	94.4	97.8	102.6	107.7	115.9
LCOE (excluding T&S) +50% TPC, $/MWh[1]	149.2	162.4	168.3	176.7	185.6	200.8
Breakeven CO_2 Sales Price, $/tonne	N/A	254	202	152	125	98
Breakeven CO_2 Sales Price -25% TPC, $/tonne[1]	N/A	191	153	115	96	75
Breakeven CO_2 Sales Price +50% TPC, $/tonne[1]	N/A	380	301	225	184	144
Breakeven CO_2 Emissions Penalty, $/tonne	N/A	261	222	178	154	128
Breakeven CO_2 Emissions Penalty -25% TPC, $/tonne[1]	N/A	199	170	138	120	101
Breakeven CO_2 Emissions Penalty +50% TPC, $/tonne[1]	N/A	386	325	259	221	183

[1]The accuracy range is applied at the TPC level, which has a consequent impact on the fixed and variable O&M costs. [6]

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