U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

OFFICE OF FOSSIL ENERGY

Cost and Performance Baseline for Fossil Energy Plants Supplement: Sensitivity to CO_2 Capture Rate in Coal-Fired Power Plants

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Disclaimer

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Acronyms and Abbreviations

AEO	Annual Energy Outlook
ASU	Air separation unit
BB	Bituminous Baseline
BFD	Block flow diagram
Btu	British thermal units
CCF	Capital charge factor
CCS	Carbon capture and sequestration
CO	Carbon monoxide
CO_2	Carbon dioxide
COE	Cost of electricity
COS	Carbonyl sulfide
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ES	Executive summary
ESPA	Energy Sector Planning and Analysis
FD	Forced draft
FGD	Flue gas desulfurization
GEE	General Electric Energy
GHG	Greenhouse gas
Gpm	Gallons per minute
h, hr	Hour
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
ISO	International Standards Organization
kg	Kilogram
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
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
LP	Low pressure
MMBtu	Million British thermal units
MW, MWe	Megawatt electric
MWh	Megawatt-hour
MWt	Megawatt thermal
NETL	National Energy Technology Laboratory
NOAK	n^{th}-of-a-kind
NOx	Nitrogen oxide
O_2	Oxygen
PA	Primary air
PC	Pulverized coal
PFD	Process flow diagram
PM	Particulate matter
psia	Pound per square inch absolute
QGESS	Quality Guidelines for Energy System Studies
R&D	Research and development
RD&D	Research, development, and demonstration
SC	Supercritical
SC PC	Supercritical pulverized coal
SCR	Selective catalytic reduction process or equipment
SDA	Spray dryer absorber
SO_2	Sulfur dioxide
SOx	Oxides of sulfur
T&S	Transport and storage
TBtu	Trillion British thermal units
TOC	Total overnight cost
tonne	Metric ton (1,000 kg)
TPC	Total plant cost
U.S.	United States
WGS	Water gas shift
°F	Degrees Fahrenheit

Executive Summary

The cost and performance of various plants designed to meet a range of carbon dioxide (CO_2) emissions 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 from the National Energy Technology Laboratory's (NETL) report "Cost and Performance Baseline for Fossil Energy Plants, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3" [1] and the General Electric Energy (GEE) integrated gasification combined cycle (IGCC) plant in NETL's report, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1b: Bituminous Coal (IGCC) to Electricity, Revision 2 – Year Dollar Update." [2] The chosen SC PC plants were based on the 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 step to be directed towards the stack, which reduces the amount CO_2 captured in the Cansolv process. The chosen IGCC plants were based on the Case B5B, differing by bypassing (either partially or entirely) the water gas shift reactors and thereby reducing the amount of CO_2 captured in the Selexol process. The major components of the underlying CO_2 capture technology in the plants were preserved with minimal modifications to the overall processes. The SC PC cases include up-to-date cost and performance information from recent vendor quotes whereas the IGCC performance and cost are based upon the older quotes used for the Revision 2 report, with standard adjustments made to update the costs to 2011 dollars.

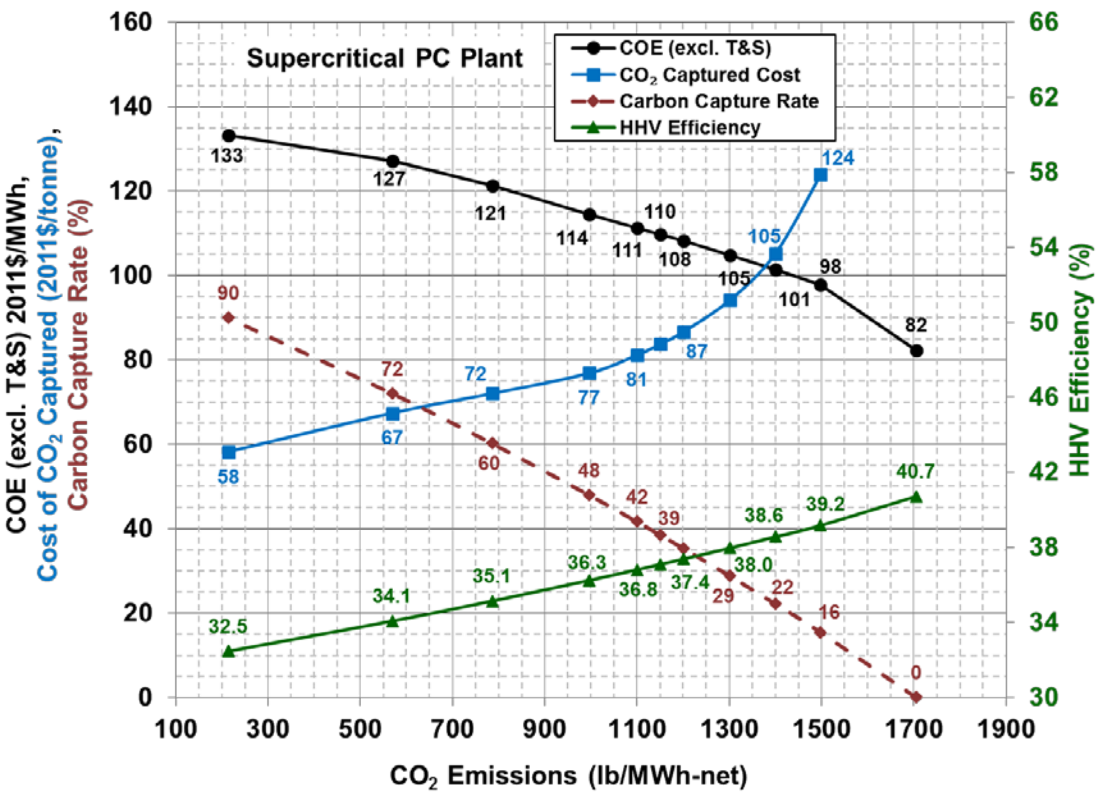
The results of the study for the SC PC and IGCC plants are summarized in Exhibit ES-1 and Exhibit ES-2, respectively. The exhibits depict the variations of the computed plant higher heating value (HHV) efficiencies, costs of electricity (COE), and costs of CO_2 captured with partial capture design CO_2 emission levels. The overall CO_2 capture rate is also shown in the exhibits. 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 a value of 32.5 percent for the SC PC plant with 90 percent CO_2 capture to a value of 40.7 percent for the SC PC plant with highest CO_2 emission (no carbon capture). The HHV efficiency of the IGCC plants vary from a value of 32.6 percent for the IGCC plant with 90 percent CO_2 capture to a value of 39.0 percent for the IGCC plant with the highest CO_2 emission (no carbon capture). The plant COE 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 COE for the plant featuring 90 percent CO_2 capture is ~ 62 percent higher than the COE of the plant with no CO_2 capture. For the IGCC plants, the COE for the plant featuring 90 percent CO_2 capture is ~ 32 percent higher than the COE of the IGCC plant with no CO_2 capture. The capture impact is smaller for the IGCC plants because the CO_2 is at a higher concentration and pressure in the IGCC syngas than in the SC PC flue gas.

Actual average annual emissions from operating plants are likely to be higher than the design emissions rates shown 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 future regulations; however, given that the slope of the variation of COE with CO_2 emission levels is not steep for either SC PC or IGCC plants (except at low capture rates), designing for this margin does not have major cost implications.

The cost of capture, equivalent to the minimum plant gate sales price (revenue) required to incentivize CO_2 capture relative to a non-capture SC PC, 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.

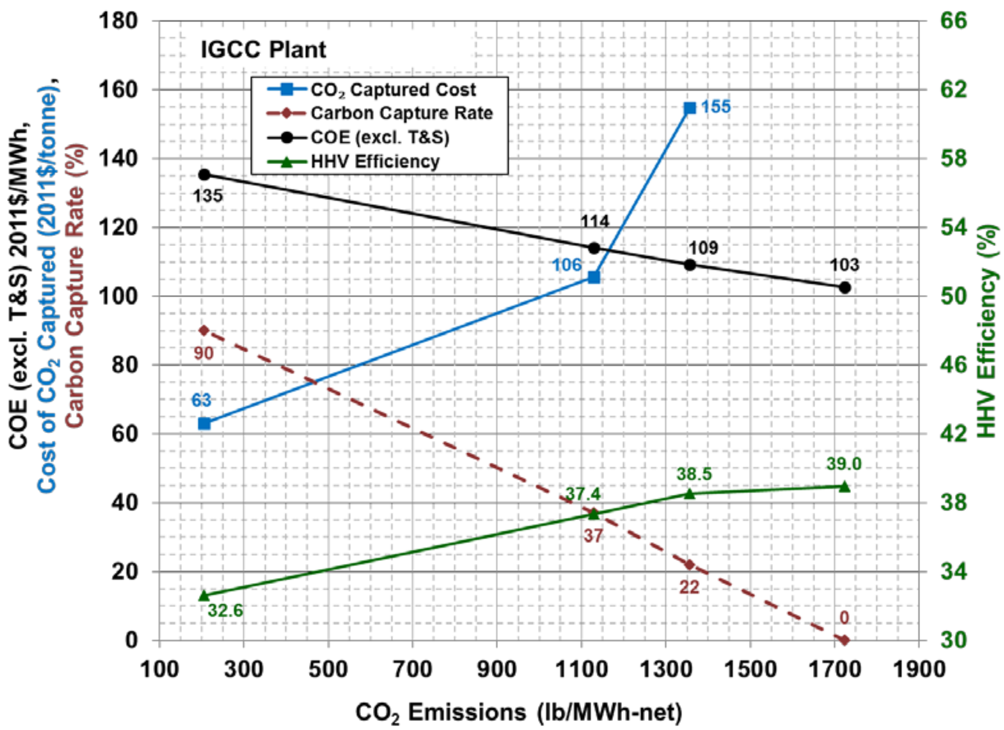
The observations in this document are made with the caveat that the differences in costs between cases are less than the absolute accuracy of the capital cost estimates (estimated to be -15 percent/+30 percent); however, all cases were evaluated using a common set of technical and economic assumptions, which allowed meaningful comparisons among the cases.

Exhibit ES-1 Variation of COE, plant HHV efficiency, cost of CO_2 captured, and CO_2 capture rate with design emission levels for SC PC cases



Source: NETL/Department of Energy (DOE)

Exhibit ES-2 Variation of COE, plant HHV efficiency, cost of CO_2 captured, and CO_2 capture rate with design emission levels for IGCC cases



Source: NETL/DOE

Exhibit ES-3 Summary of results

Plant type	CO_2 Emission Level		CO_2 Capture Rate	HHV Efficiency	*COE (excl. T&S)	**Cost of Captured CO_2	**Cost of Avoided CO_2
	lb/MWh-gross	lb/MWh-net	%	%	$/MWh	$/tonne CO_2	$/tonne CO_2
SC PC	1,618	1,705	0	40.7	82.3	-	-
	1,400	1,498	16	39.2	97.8	123.9	178.7
	1,300	1,400	22	38.6	101.4	105.3	152.6
	1,200	1,302	29	38.0	104.8	94.2	137.4
	1,100	1,201	35	37.4	108.1	86.7	127.2
	1,050	1,151	39	37.1	109.7	83.7	123.2
	1,000	1,100	42	36.8	111.3	81.2	119.7
	900	997	48	36.3	114.4	76.9	114.0
	700	786	60	35.1	121.2	72.0	107.5
	500	570	72	34.1	127.2	67.4	101.4
	183	214	90	32.5	133.2	58.2	89.4
IGCC	1,434	1,724	0	39.0	102.6	-	-
	1,100	1,356	22	38.5	109.3	154.7	182.4
	900	1,129	37	37.4	114.2	105.7	134.8
	152	206	90	32.6	135.4	63.2	91.7

*Cases without capture use conventional financing; all others use high-risk financial assumptions, consistent with Reference. [1] [2] [5]

**Cost of capture based on SC PC without capture (Case B12A)

Special Considerations on Reported Costs

Capital Costs:

The capital cost estimates documented in this report reflect an uncertainty range of -15%/+30%, consistent with AACE Class 4 cost estimates (i.e., feasibility study) [3] [4] [5], 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 which 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 R&D.

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:

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

Future Cost Trends:

Continuing research, development, and demonstration (RD&D) 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.

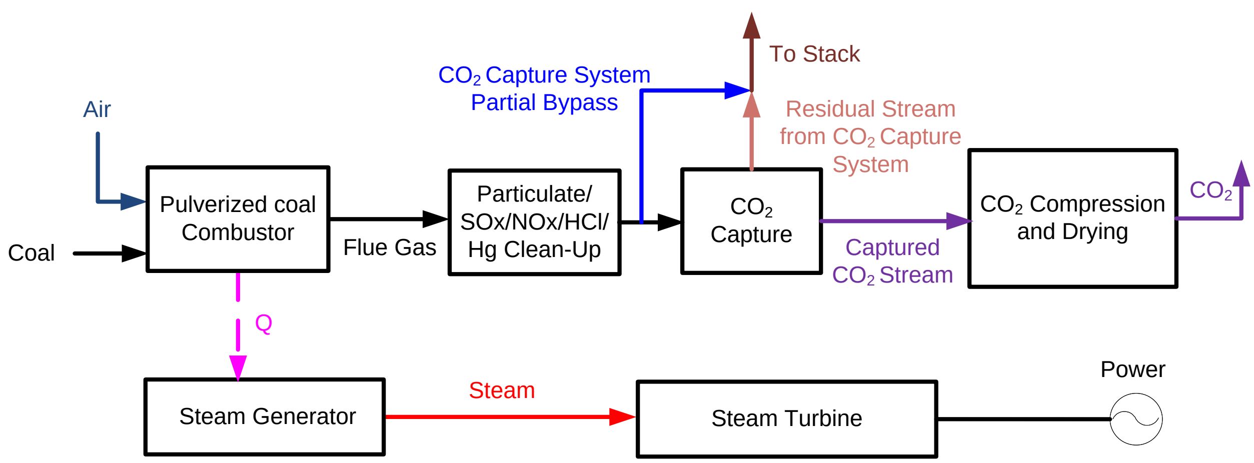
1 Introduction

The National Energy Technology Laboratory's (NETL) Bituminous Baseline (BB) studies [1] [2] have 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 at least 90 percent carbon capture. The cost and performance of coal-based BB 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 BB supercritical (SC) pulverized coal (PC) plant with capture (Case B12B) [1] and integrated gasification combined cycle (IGCC) plant with capture (Case B5B) [2], both modified to achieve various levels of partial capture. The partial capture cases presented in this report preserve the major components of the underlying carbon capture and sequestration (CCS) technology utilized in the corresponding BB plants with minimal modifications to the overall processes.

In the SC PC cases, an appropriate portion of the flue gas stream exiting the desulfurization step is diverted, as shown in Exhibit 1-1, to the stack, bypassing the CO_2 capture system, in order to evaluate systems with CO_2 emissions ranging from ~ 1700 – 210 lb/MWh-net (zero to 90 percent capture). 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, as in the B12B case.

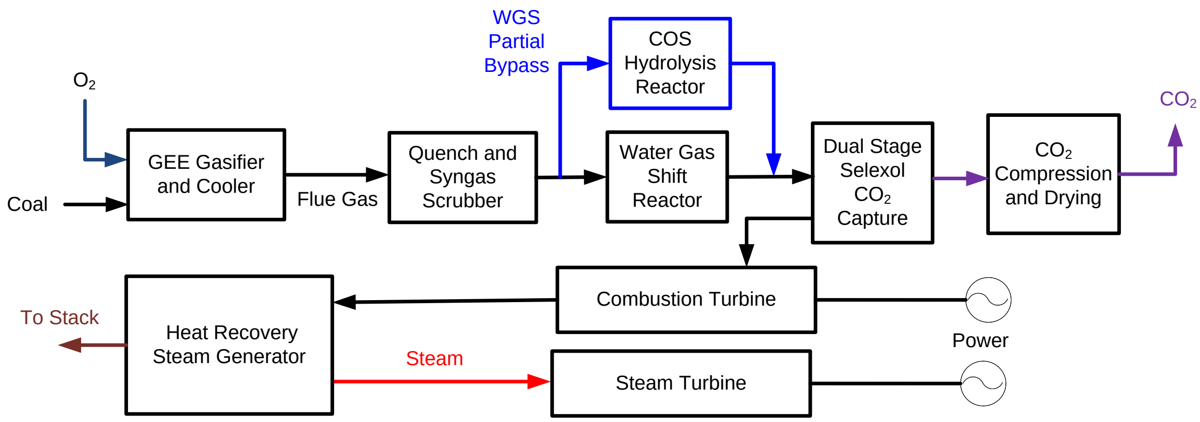
Exhibit 1-1 Bituminous Baseline SC PC schematic – modifications for partial capture cases



Source: NETL/Department of Energy (DOE)

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 ~ 1720 – 205 lb/MWh-net (zero to 90 percent capture). The key differences between the cases are reflected in the mole percentage of CO_2 in the feed to the dual stage Selexol unit. These values range from ~16 mole percent for the 22 percent capture case to ~40.6 mole percent for the 90 percent capture case (B5B).

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



Source: NETL/DOE

2 Design Basis

The modified plants are assumed to be a generic Midwestern United States (U.S.) plant operating under ambient International Standards Organization (ISO) conditions with site and coal characteristics that are identical to the BB plants. [1] [2] The emission targets are assumed to be the same as in the BB studies, with the exception of the CO_2 emission limit, which forms a parameter in the present investigation.

2.1 Partial Capture Calculation

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

$$\% \ CO_2 \text{ capture} = CO_2 \text{ Captured} / (CO_2 \text{ Captured} + CO_2 \text{ Emissions} * \text{Plant Output})$$

For example, in BB Case B12B is as follows:

$$90\% \ CO_2 \text{ capture} = 1{,}059{,}193 \text{ lb/hr} / (1{,}059{,}193 \text{ lb/hr} + 214 \text{ lb/MWh-net} * 550 \text{ MW})$$

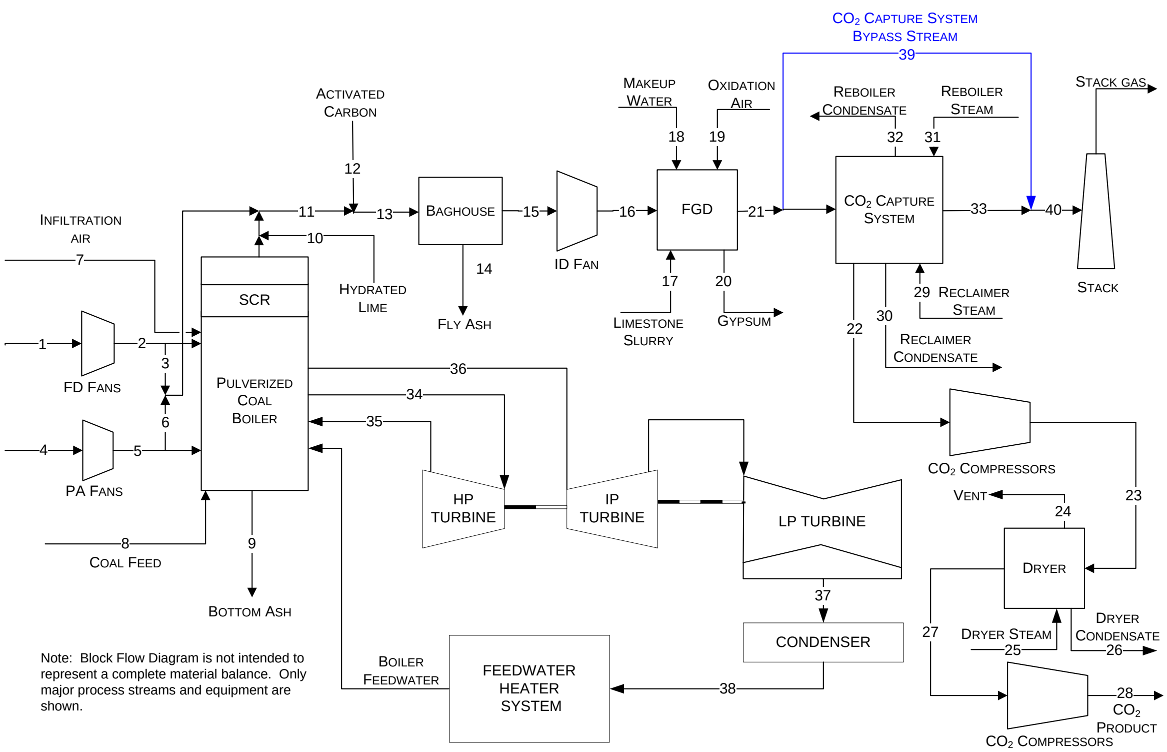
2.2 SC PC Partial Capture Design

The block flow diagram (BFD) of the modified SC PC system, shown in Exhibit 2-1, differs from the BFD of the base Case B12B only by the addition of the CO_2 capture system bypass flue gas stream, downstream of the flue gas desulfurizer (FGD), which can be tuned to meet the desired CO_2 emission level. The basis for the cost and performance of all partial capture cases is the previously mentioned Shell Cansolv amine-based system operating at 90 percent capture. No performance penalties were assessed due to the potential operation of the capture system at a scale smaller than its rated design point; accordingly, its auxiliary load was computed directly based on the CO_2 product flow rate. A power law with an exponent of 0.6 was assumed to scale

40 percent of the cost of the CO_2 capture system based on the inlet gas volumetric flow to the process and the remaining 60 percent of the cost scaled based upon the captured CO_2 mass flow rate in accordance with Quality Guidelines for Energy System Studies (QGESS) procedures. [6] The costs for controlling and monitoring the CO_2 capture system bypass flow were assumed to be negligible. 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 CCS), which is tantamount to a special subset of the modified system where all the flue gas flow bypasses the CO_2 capture system.

The plants are evaluated at a rated net power of 550 MWe with an assumed capacity factor of 85 percent. A high-risk financial structure resulting in a capital charge factor (CCF) of 0.124 is used to evaluate the costs of all cases with CO_2 capture (non-capture case uses a conventional financial structure with a CCF of 0.116).[1] All other process parameters and cost assumptions are identical to Case B12B.

Exhibit 2-1 Block flow diagram of the modified B12B process for partial capture



Source: NETL/DOE

[1] In contrast, the Energy Information Administration (EIA) applies a cost of capital premium to non-capture coal plants in its Annual Energy Outlook (AEO) Reference Cases. Specifically, "to reflect the market reaction to potential future GHG regulation, a 3-percentage-point increase in the cost of capital for investments in new coal-fired power and coal-to-liquids plants without carbon capture and sequestration technology is assumed." [5]

2.3 IGCC Partial Capture Design

The block flow diagram of the modified IGCC system, shown in Exhibit 2-2, differs from that of the BB Case B5B with 90 percent capture solely by the addition of a bypass around the WGS reactors. The bypass includes a COS hydrolysis reactor. Two partial capture cases were evaluated: one with a partial bypass of the WGS reactor and achieving 37 percent capture, and one with the WGS bypassed completely and achieving 22 percent capture.

The plants are evaluated with an assumed capacity factor of 80 percent. A high-risk financial structure resulting in a CCF of 0.124 is used to evaluate the costs of all IGCC cases. All other process parameters and cost assumptions are identical to Case B5B.

2.3.1 Water Gas Shift and COS Hydrolysis

The 37 percent capture case, resulting in 1,129 lb/MWh-net or 900 lb/MWh-gross, requires only 17 percent of the syngas to be sent to the WGS reactors. The 22 percent capture case, resulting in 1,356 lb/MWh-net or 1,100 lb/MWh-gross, can be processed without including WGS reactors, so the entire gasifier exit stream is processed through a COS hydrolysis reactor instead. The reduced flow through the WGS reactor also reduces the amount of shift steam that needs to be extracted from the steam cycle from 285,687 lb/hr of 800 psia, 550°F steam for the reference 90 percent capture case to 45,797 lb/hr in the 37 percent capture case, and zero in the 22 percent capture case. This lower steam extraction requirement results in higher gross power output from the steam cycle for the partial capture cases.

A power law with an exponent of 0.8 was assumed to scale the cost of the shift and COS hydrolysis reactors based on catalyst volume in accordance with QGESS procedures. [6]

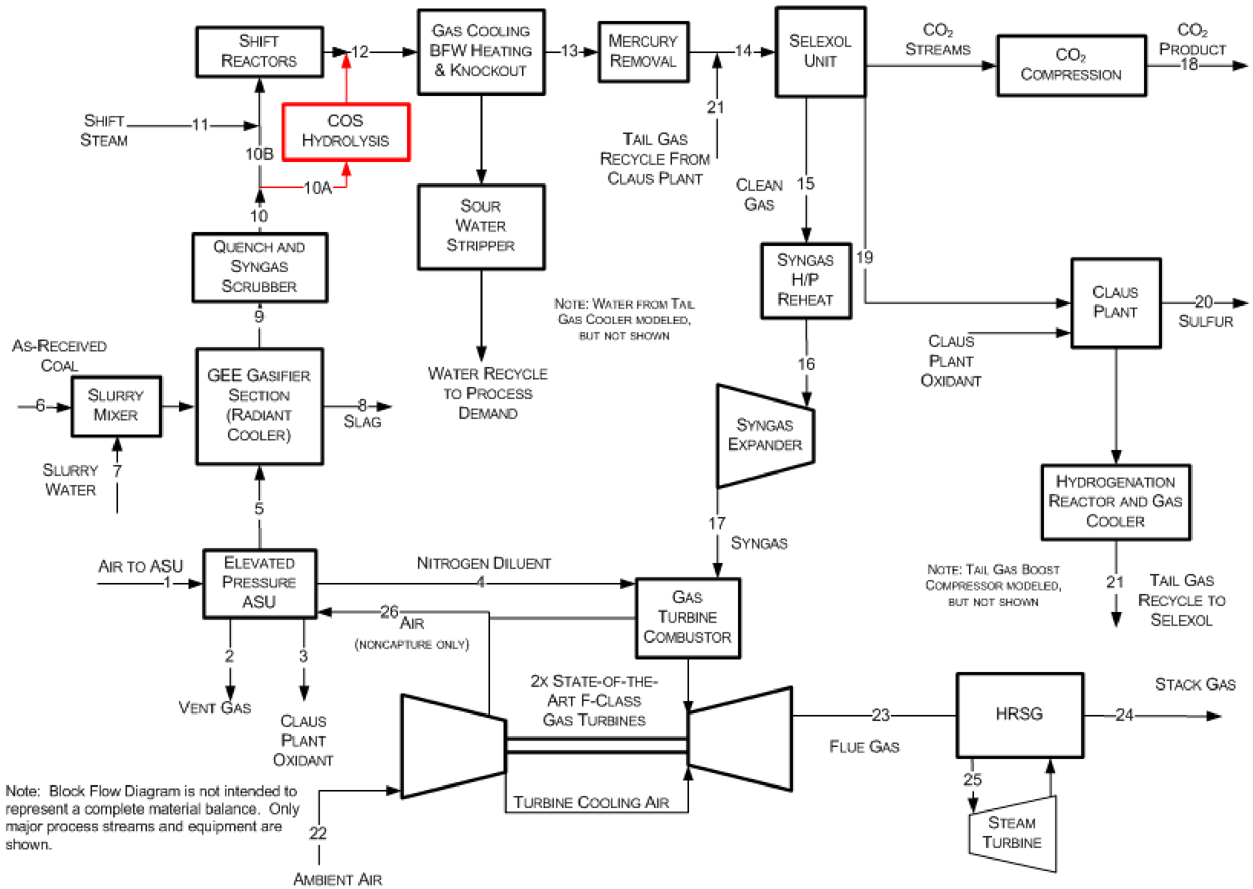
2.3.2 CO_2 Capture – Dual Stage Selexol

The amount of hydrogen recovered from the syngas stream is dependent on the Selexol process design conditions. In the BB report, hydrogen recovery is 99.4 percent. The minimal hydrogen slip to the CO_2 sequestration stream maximizes the overall plant efficiency. The BB case Selexol plant cost estimates are based on a plant designed to recover this high percentage of hydrogen.

The Selexol system is designed to capture 93 percent of the CO_2 in the feed to the dual stage process for both of the cases that require some WGS. For the lowest capture case with no WGS, the system only needs to capture 78 percent of the CO_2 in the feed to meet the proposed limit, so the cost estimates were modified to reflect the reduced capture requirement, while the performance continues to be scaled on the amount of CO_2 captured.

Since the Selexol system has components for sulfur capture as well as CO_2 capture, a combined approach to cost scaling was utilized. A power law with an exponent of 0.79 was assumed to scale 40 percent of the cost of the dual stage Selexol system based on the inlet gas volumetric flow to the process while a power law with an exponent of 0.61 was used to scale the remaining 60 percent of the cost based upon the captured CO_2 flow rate in accordance with QGESS procedures. [6]

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



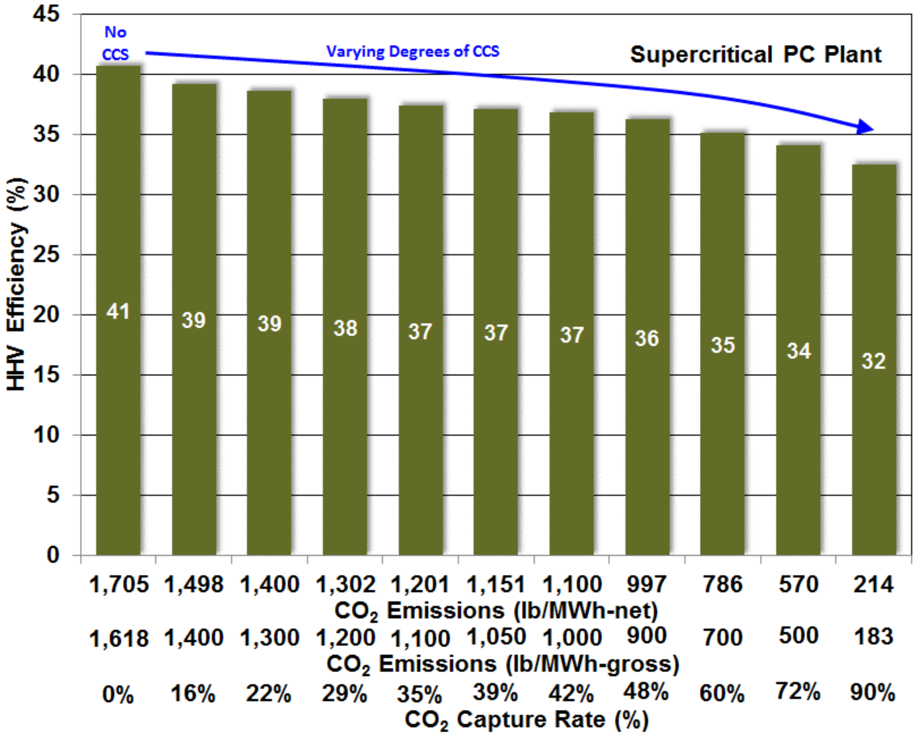
Source: NETL/DOE

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 percent 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. Detailed performance and cost data is found in the Appendix to this report.

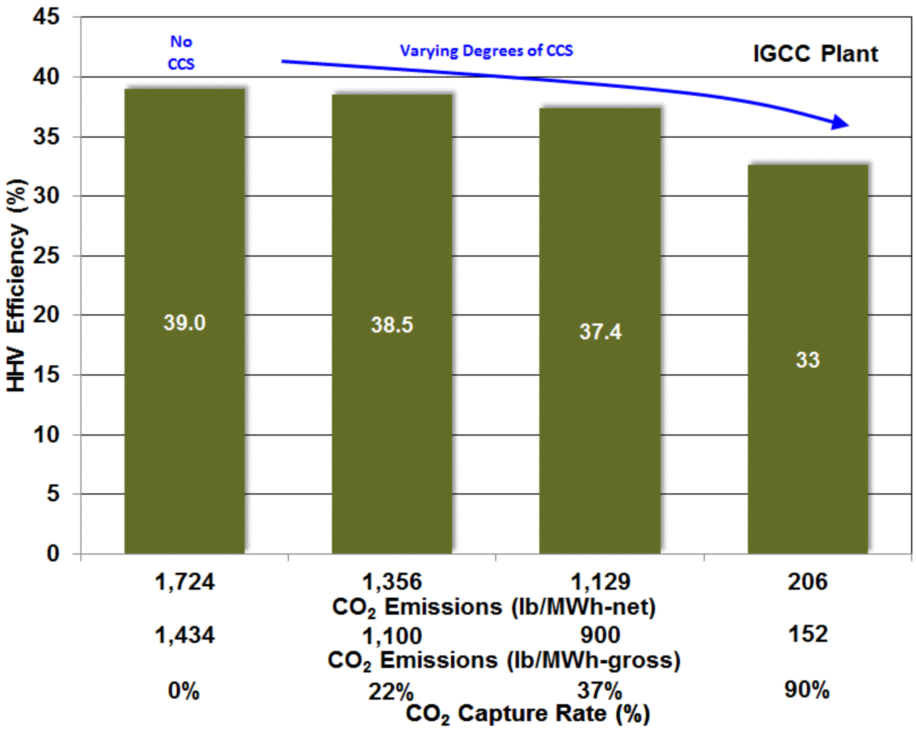
The variations of the cost of electricity (COE) for different design values of CO_2 emissions are shown in Exhibit 3-3 and 3-4. The COE increases gradually as the capture rate increases. The costs of CO_2 captured and avoided using the BB SC PC non-capture case (B12B) as the reference case are shown in Exhibits 3-5 and 3-6. The cost of captured CO_2 represents the minimum CO_2 plant gate sales price that will incentivize carbon capture in lieu of a defined reference non-capture plant. Similarly, the cost of avoided CO_2 represents the minimum cost of, or penalty on, CO_2 emissions that will incentivize the carbon capture cases in lieu of a non-capture plant. For both the SC PC and the IGCC cases, the non-capture SC PC case (B12A) as the lowest cost non-capture coal case serves as the reference plant. As the figures indicate, the normalized capture and avoided costs decrease significantly as the capture rate increases due to the economies of scale and the increasing amount of CO_2 captured or avoided.

Exhibit 3-1 Plant HHV Efficiency for SC PC plant at various levels of capture



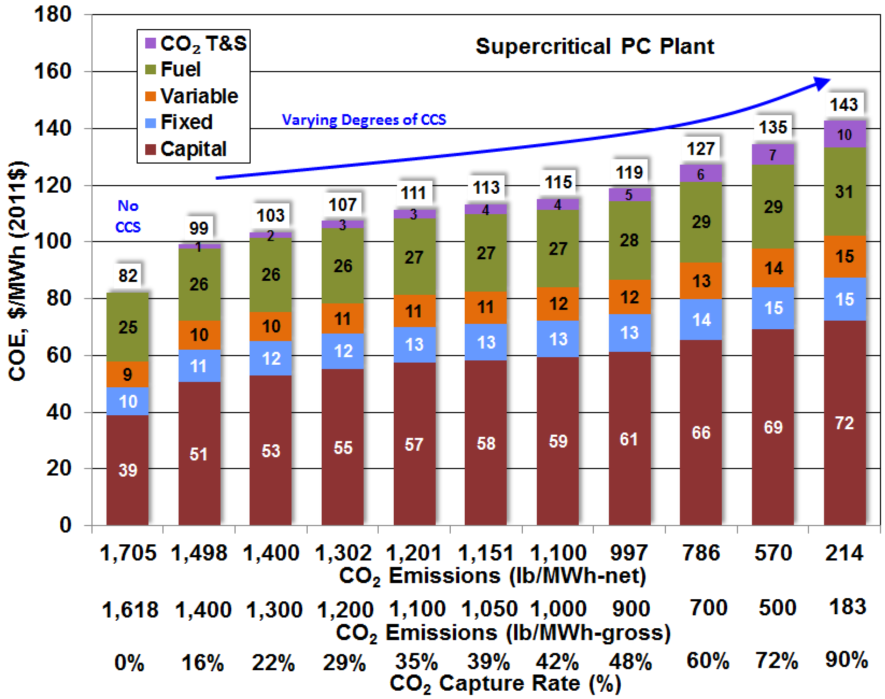
Source: NETL/DOE

Exhibit 3-2 Plant HHV Efficiency for IGCC plant at various levels of capture



Source: NETL/DOE

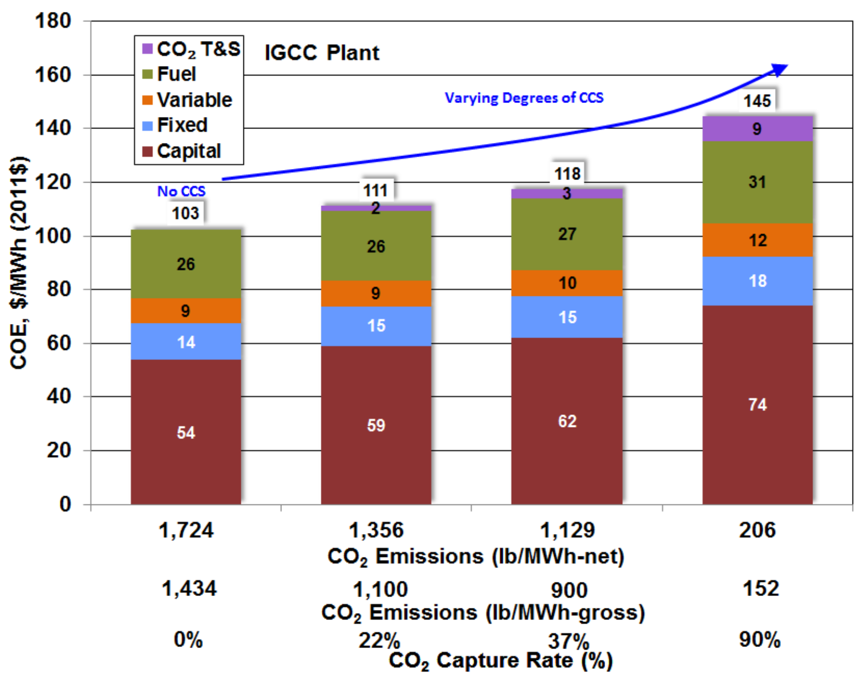
Exhibit 3-3 COE with T&S for SC PC plant at various levels of capture



Note: Case without capture uses conventional financing. All others use high-risk financial assumptions.

Source: NETL/DOE

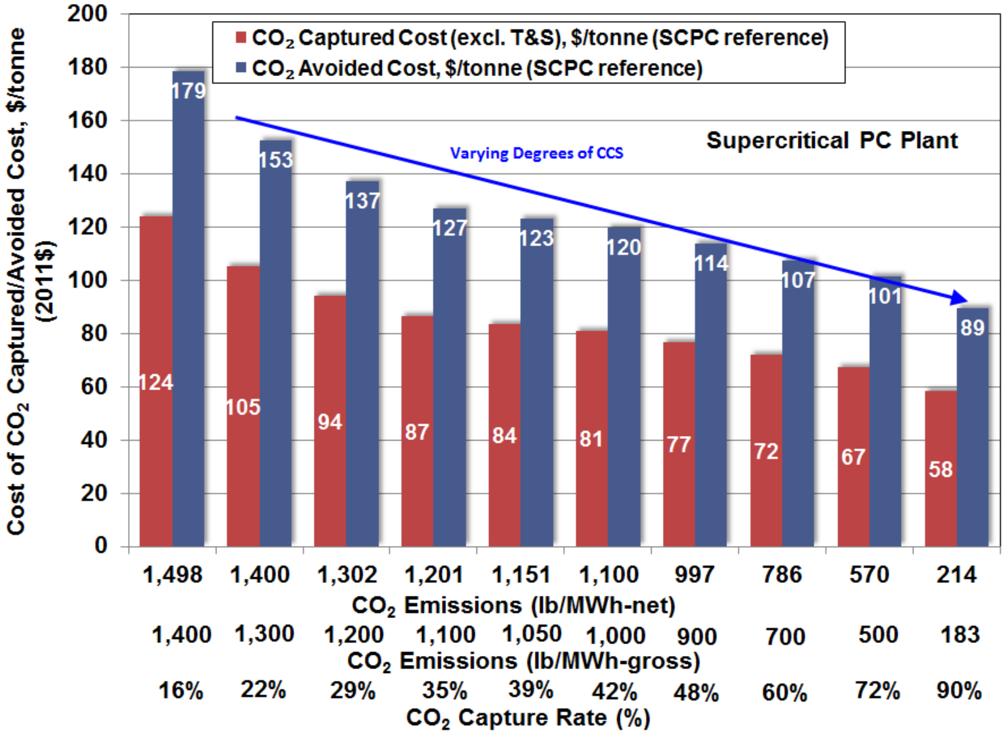
Exhibit 3-4 COE with T&S for IGCC plant at various levels of capture



Note: Case without capture uses conventional financing. All others use high-risk financial assumptions.

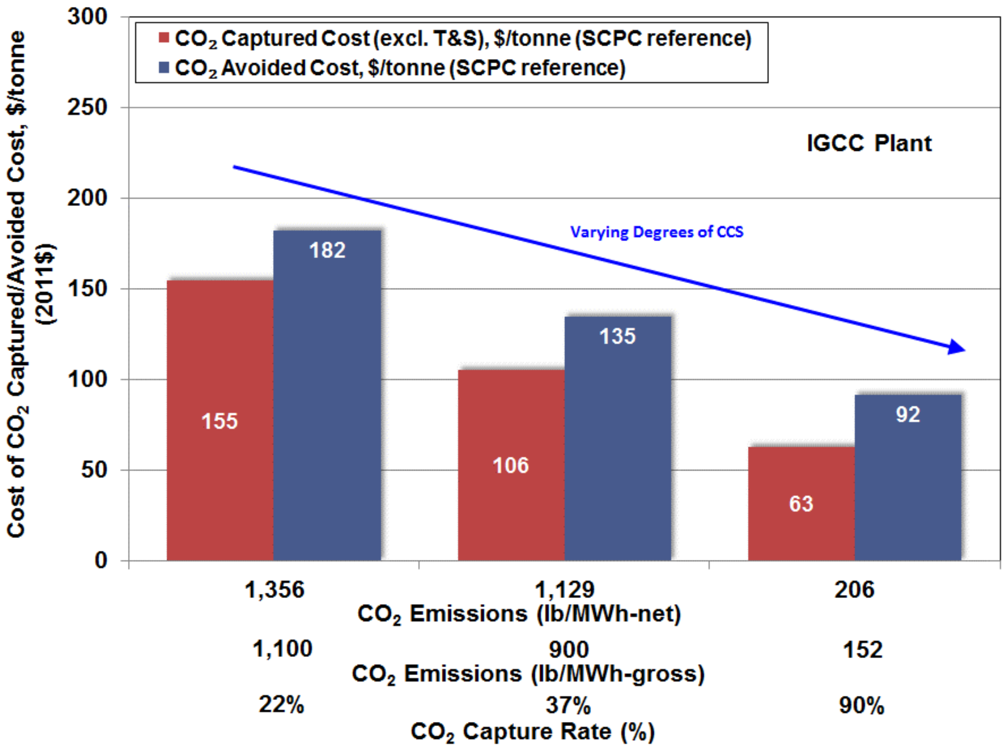
Source: NETL/DOE

Exhibit 3-5 Cost of captured and avoided CO_2 for SC PC plant at various levels of capture



Source: NETL/DOE

Exhibit 3-6 Cost of captured and avoided CO_2 for IGCC plant at various levels of capture



Source: NETL/DOE

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

$$\text{Capture Energy Penalty} = \frac{\left(\frac{1}{HeatRate_{HHVnon-capture}} - \frac{1}{HeatRate_{HHVcapture}}\right) * 1{,}000{,}000}{(\%\text{Capture} \ * \ \text{CO}_2 \text{ Emissions Factor in lb/MMBtu of fuel input})}$$

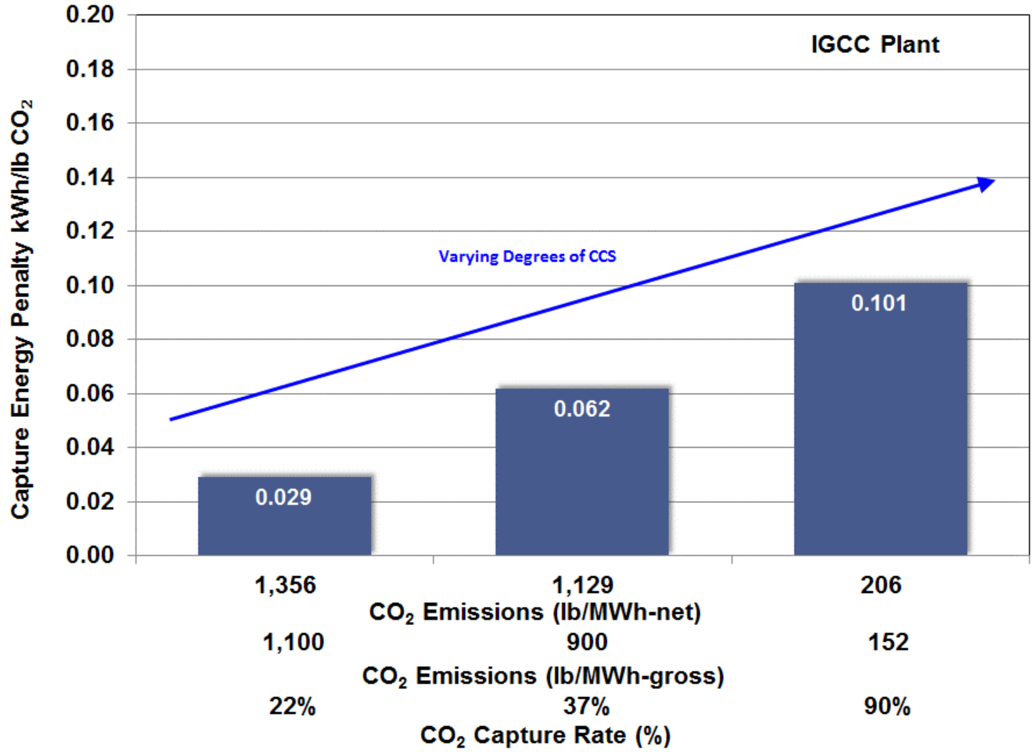
Where:

CO_2 Emissions Factor = 204 lb/MMBtu for bituminous coal

The capture energy penalties for the SC PC capture cases are nearly constant with a value of approximately 0.14 kWh/lb CO_2. This is due to the use of the bypass around the CO_2 capture system. All cases represent the use of a 90 percent efficient CO_2 capture system with flue gas feed streams proportional to the desired overall CO_2 capture rate.

The capture energy penalties for the three IGCC capture cases in this study are shown in Exhibit 3 and illustrate that the penalty increases significantly with increasing capture rates. The increasing capture penalty with higher rates of capture is due to the addition and intensification of unit operations at each level. The 22 percent capture case does not have WGS. The 37 percent capture case adds some WGS and, therefore, has a larger energy penalty. 90 percent capture requires a larger amount of WGS and a higher capture rate in the Selexol unit and, therefore, has the highest capture energy penalty.

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



Source: NETL/DOE

4 Conclusion

SC PC plants that meet a range of design CO_2 emission levels were developed by modifying the SC PC plant with CCS (case B12B) through the introduction of flue gas bypass of the CO_2 capture system. IGCC plants that meet a range of design CO_2 emission levels were developed by modifying the IGCC plant with CCS (case B5B) through the introduction of syngas bypass of the WGS reactor to reduce the amount of CO_2 in the stream to the capture system. For both the SC PC and IGCC plants, lower levels of CO_2 capture result in a lower COE, 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. The cost of capture, equivalent to the minimum plant gate CO_2 sales price (revenue) required to incentivize CO_2 capture relative to a non-capture SC PC, 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 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3.* Pittsburgh, Pa : U.S. Department of Energy, 2015.

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Appendix

Key Performance and Cost Summary Tables

Exhibit A-1 PC cases performance summary

	Case B12A	Partial Capture Cases									Case B12B
CO_2 Capture Rate	**0%**	**16%**	**22%**	**29%**	**35%**	**39%**	**42%**	**48%**	**60%**	**72%**	**90%**
Capacity Factor	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Gross Power Output (MWe)	580	589	592	597	600	603	605	609	618	626	642
Auxiliary Power Requirement (MWe)	30	38	42	46	50	53	55	59	68	77	91
Net Power Output (MWe)	550	550	550	550	550	550	550	550	550	550	550
Coal Flow rate (lb/hr)	395,053	410,912	417,178	423,717	430,079	433,533	436,873	443,675	457,667	471,919	495,578
HHV Thermal Input (kW_t)	1,350,672	1,404,894	1,426,316	1,448,676	1,470,427	1,482,236	1,493,655	1,516,909	1,564,750	1,613,476	1,694,366
Net Plant HHV Efficiency (%)	40.7%	39.2%	38.6%	38.0%	37.4%	37.1%	36.8%	36.3%	35.1%	34.1%	32.5%
Net Plant HHV Heat Rate (Btu/kWh)	8,379	8,710	8,848	8,986	9,126	9,197	9,269	9,413	9,708	10,012	10,508
Raw Water Withdrawal, gpm	5,105	5,533	5,710	5,891	6,072	6,166	6,259	6,448	6,835	7,231	7,882
Process Water Discharge, gpm	1,059	1,174	1,222	1,271	1,321	1,346	1,372	1,423	1,528	1,636	1,813
Raw Water Consumption, gpm	4,045	4,359	4,488	4,620	4,751	4,820	4,888	5,025	5,307	5,595	6,069
CO_2 Emissions (lb/MMBtu)	204	172	158	145	132	125	119	106	81	57	20
CO_2 Emissions (lb/MWhgross)	**1,618**	**1,400**	**1,300**	**1,200**	**1,100**	**1,050**	**1,000**	**900**	**700**	**500**	**183**
CO_2 Emissions (lb/MWhnet)	**1,705**	**1,498**	**1,400**	**1,302**	**1,201**	**1,151**	**1,100**	**997**	**786**	**570**	**214**
SO_2 Emissions (lb/MMBtu)	0.085	0.070	0.064	0.058	0.051	0.048	0.045	0.040	0.028	0.017	0.000
SO_2 Emissions (lb/MWhgross)	0.673	0.570	0.523	0.477	0.430	0.406	0.383	0.336	0.242	0.148	0.000
NOx Emissions (lb/MMBtu)	0.088	0.086	0.085	0.084	0.084	0.083	0.083	0.082	0.081	0.080	0.078
NOx Emissions (lb/MWhgross)	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700
PM Emissions (lb/MMBtu)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	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	0.090	0.090	0.090
Hg Emissions (lb/TBtu)	0.377	0.368	0.365	0.362	0.359	0.357	0.356	0.353	0.347	0.341	0.333
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	3.00E-06	3.00E-06	3.00E-06

Exhibit A-2 IGCC cases performance summary

	Case B5A	Partial Capture		Case B5B
CO_2 Capture Rate	**0%**	**22%**	**37%**	**90%**
Capacity Factor	80%	80%	80%	80%
Gross Power Output (MWe)	748	752	747	734
Auxiliary Power Requirement (MWe)	126	142	152	191
Net Power Output (MWe)	622	610	595	543
Coal Flow rate (lb/hr)	466,898	463,138	466,131	487,005
HHV Thermal Input (kW_{th})	1,596,309	1,583,454	1,593,685	1,665,056
Net Plant HHV Efficiency (%)	39.0%	38.5%	37.4%	32.6%
Net Plant HHV Heat Rate (Btu/kWh)	8,758	8,860	9,133	10,459
Raw Water Withdrawal, gpm	4,755	4,685	4,905	5,834
Process Water Discharge, gpm	984	968	994	1,080
Raw Water Consumption, gpm	3,771	3,717	3,911	4,754
CO_2 Emissions (lb/MMBtu)	197	153	124	20
CO_2 Emissions (lb/MWhgross)	**1,434**	**1,100**	**900**	**152**
CO_2 Emissions (lb/MWhnet)	**1,724**	**1,356**	**1,129**	**206**
SO_2 Emissions (lb/MMBtu)	0.001	0.002	0.002	0.002
SO_2 Emissions (lb/MWhgross)	0.009	0.016	0.016	0.017
NOx Emissions (lb/MMBtu)	0.059	0.055	0.054	0.049
NOx Emissions (lb/MWh_{gross})	0.430	0.396	0.394	0.376
PM Emissions (lb/MMBtu)	0.007	0.007	0.007	0.007
PM Emissions (lb/MWh_{gross})	0.052	0.051	0.052	0.055
Hg Emissions (lb/TBtu)	0.412	0.417	0.412	0.388
Hg Emissions (lb/MWh_{gross})	3.00E-06	3.00E-06	3.00E-06	3.00E-06

Exhibit A-3 PC cases cost summary

	Case B12A	Partial Capture Cases									Case B12B
CO_2 Capture Rate	**0%**	**16%**	**22%**	**29%**	**35%**	**39%**	**42%**	**48%**	**60%**	**72%**	**90%**
Total Plant Cost (2011$/kW)	2,026	2,467	2,586	2,695	2,798	2,847	2,896	2,990	3,204	3,384	3,524
Bare Erected Cost	1,646	1,955	2,040	2,117	2,190	2,225	2,260	2,327	2,481	2,610	2,716
Home Office Expenses	165	193	200	207	214	217	220	226	241	252	263
Project Contingency	216	279	297	312	327	334	341	355	386	411	430
Process Contingency	0	39	49	58	67	71	74	82	96	110	115
Total Overnight Cost (2011$MM)	1,379	1,674	1,753	1,826	1,894	1,928	1,960	2,023	2,167	2,287	2,384
Total Overnight Cost (2011$/kW)	2,507	3,042	3,187	3,320	3,445	3,505	3,565	3,680	3,940	4,160	4,333
Owner's Costs	480	575	601	625	647	658	669	689	736	776	809
Total As-Spent Capital (2011$/kW)	2,842	3,468	3,633	3,784	3,928	3,996	4,064	4,195	4,492	4,742	4,940
COE ($/MWh) (excluding T&S)	82.3	97.8	101.4	104.8	108.1	109.7	111.3	114.4	121.2	127.2	133.2
Capital Costs	39.0	50.7	53.1	55.3	57.4	58.4	59.4	61.3	65.6	69.3	72.2
Fixed Costs	9.6	11.5	11.9	12.3	12.7	12.9	13.1	13.4	14.2	14.9	15.4
Variable Costs	9.1	10.1	10.5	10.9	11.3	11.4	11.6	12.0	12.8	13.6	14.7
Fuel Costs	24.6	25.6	26.0	26.4	26.8	27.0	27.2	27.7	28.5	29.4	30.9
COE ($/MWh) (including T&S)	82.3	99.1	103.7	107.5	111.4	113.3	115.2	119.0	127.1	134.5	142.8
CO_2 T&S Costs	0.0	1.4	2.0	2.6	3.3	3.6	3.9	4.6	5.9	7.3	9.6
COE Range Reflecting Capital Cost Accuracy*											
COE ($/MWh) (excluding T&S) -15% TPC	75.8	90.7	94.6	98.3	101.9	103.6	105.4	108.8	116.2	123.0	130.8
COE ($/MWh) (excluding T&S) + 30% TPC	95.3	115.9	121.0	125.8	130.5	132.7	134.9	139.3	148.9	157.6	166.8
CO_2 Captured Cost (excluding T&S), $/tonne	N/A	123.9	105.3	94.2	86.7	83.7	81.2	76.9	72	67.4	58.2
CO_2 Avoided Cost (including T&S), $/tonne	N/A	178.7	152.6	137.4	127.2	123.2	119.7	114	107.5	101.4	89.4

*The accuracy range is applied at the Total Plant Cost (TPC) level, which has a consequent impact on the fixed and variable O&M costs. [6]

Exhibit A-4 IGCC cases cost summary

	Case B5A	**Partial Capture**		**Case B5B**
CO_2 Capture Rate	**0%**	**22%**	**37%**	**90%**
Total Plant Cost (2011$/kW)	2,449	2,707	2,839	3,387
Bare Erected Cost	1,870	2,029	2,125	2,525
Home Office Expenses	187	203	213	253
Project Contingency	330	366	386	467
Process Contingency	61	109	115	143
Total Overnight Cost (2011$MM)	1,888	2,036	2,086	2,279
Total Overnight Cost (2011$/kW)	3,036	3,339	3,503	4,195
Owner's Costs	587	632	664	807
Total As-Spent Capital (2011$/kW)	3,461	3,807	3,994	4,782
COE ($/MWh) (excluding T&S)	102.6	109.3	114.2	135.4
Capital Costs	53.7	59.1	62.0	74.2
Fixed Costs	13.7	14.8	15.5	18.2
Variable Costs	9.4	9.4	9.9	12.2
Fuel Costs	25.7	26.0	26.8	30.7
COE ($/MWh) (including T&S)	102.6	111.2	117.5	144.7
CO_2 T&S Costs	0.0	1.9	3.3	9.2
COE Range Reflecting Capital Cost Accuracy*				
COE ($/MWh) (excluding T&S) -15% TPC	93.7	101.4	107.3	132.4
COE ($/MWh) (excluding T&S) + 30% TPC	120.3	130.8	138.1	169.2
CO_2 Captured Cost (excluding T&S), $/tonne	N/A	154.7	105.7	63.2
CO_2 Avoided Cost (including T&S), $/tonne	N/A	182.4	134.8	91.7

*The accuracy range is applied at the Total Plant Cost (TPC) level, which has a consequent impact on the fixed and variable O&M costs. [6]

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