NATIONAL ENERGY TECHNOLOGY LABORATORY

METHODOLOGY FOR ESTIMATING PERFORMANCE AND COST OF NATURAL GAS COMBINED CYCLE PLANTS WITH CARBON CAPTURE

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Disclaimer

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ACRONYMS AND ABBREVIATIONS

$	U.S. dollars
°F	Degrees Fahrenheit
%	Percent
BFW	Boiler feedwater
CCF	Capital charge factor
CF	Capacity factor
CO_2	Carbon dioxide
COE	Cost of electricity
CPU	CO_2 compression and purification/drying unit
DOE	Department of Energy
FEB	Fossil Energy Baseline studies
FO&M	Fixed operation and maintenance
h, hr	Hour
HHV	Higher heating value
HP	High pressure
HRSG	Heat recovery steam generator
IP	Intermediate pressure
kg	Kilograms per hour
kW	Kilowatt
lb	Pound
lbmole	Pound moles
MMBtu	Million British thermal units
MPa	Megapascal
MW	Megawatt
MWe	Megawatt electric
MWh	Megawatt-hour
N/A	Not applicable
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
O&M	Operation and maintenance
PC	Pulverized coal
ppmv	Parts per million volume
psia	Pound per square inch absolute
psig	Pound per square inch gage
QGESS	Quality Guidelines for Energy System Studies
RH	Reheat
SH	Superheated
T&S	Transport and storage
TEG	Triethylene glycol
TOC	Total overnight cost
tonne	Metric ton (1,000 kg)
TPC	Total plant cost
tph	Short ton per hour
U.S.	United States
VO&M	Variable operation and maintenance
y, yr	Year

1 INTRODUCTION

This document describes a methodology that allows developers and evaluators to assess the status of developmental, natural gas combined cycle (NGCC) power plant post-combustion carbon dioxide (CO_2) separation technologies with respect to performance and cost metrics. Developmental CO_2 separation technologies that might apply for NGCC post-combustion power generation can be placed into several categories, including, but not limited to the following:

- CO_2-membranes
- CO_2-solvents
- CO_2-sorbents
- CO_2-adsorbents
- CO_2-phase-change

To support the development of CO_2 separation technologies, a common application basis is required, and tools are needed that can quickly assess new test results, new CO_2 separation process enhancements, and updated CO_2 separation equipment performance and cost estimates to project the performance and cost of a base NGCC power plant utilizing the CO_2 separation technology. The Department of Energy (DOE) National Energy Technology Laboratory (NETL) developed a methodology and associated tools for pulverized coal (PC) plants that were used as a guide in developing the similar methodology and tool—for NGCC plants—discussed in this document. [1]

Within the fossil energy baseline studies (FEB), the PC plant designs and costs are based on retaining a fixed 650 MW_{net} plant power generation. [2] Adding capture systems to the base PC plant design significantly alters the performance and equipment sizes of the base plant, including the coal feed and flue gas flow rates, required to maintain the 650 MW_{net} generation. The costs are increased by both the capture system and the significant alterations in the base plant design. The methodology applied to PC plants necessitated developing complex factors for use within the PC tool. [1] The addition of a capture system to an NGCC plant does not significantly alter the base plant beyond steam turbine and cooling tower changes because the majority of the base plant design is fixed by the combustion turbine model selection. The net plant power generation changes based on the steam, cooling, and auxiliary power requirements of the CO_2 processing technologies. The methodology developed for the NGCC plants uses a simplified factoring and scaling approach within the NGCC tool that is detailed in this document.

Key components in the NGCC power plant are influenced by a CO_2 capture process, these being the steam turbine power generation system and the cooling water system. The CO_2 capture process is broken into two major systems: 1) the <u>CO_2 separation system</u>, representing the developmental CO_2 separation technologies, and 2) the <u>CO_2 compression and purification/drying unit</u> (CPU) system. A CPU tool based on partial condensation and distillation processing integrated with the compression was developed for use with the PC methodology and modified for use with the NGCC methodology. [3] The CO_2 separation technology developers can also use their own technology-specific system for the CPU performance and costs estimates within this NGCC methodology.

Section 2 of this document identifies two base non-capture NGCC power plants and the fixed plant configurations and environments into which developmental CO_2 capture processes can operate. Process boundaries and constraints for post-combustion CO_2 capture processes are specified, establishing an assessment basis for CO_2 separation technology process developers. The base NGCC power plants are taken from the FEB Revision 4a, Case B31A (F-Frame turbines) and Case B32A (H-Frame turbines) NGCC plant representations. The FEB provides additional cases with Shell CANSOLV CO_2 capture technology added to the two base NGCC plants at three capture rates (i.e., 90, 95, and 97 percent) that are used for comparison as well as scaling within the NGCC methodology. [2]

Section 3 discusses the methodology for estimating the impact of a developmental CO_2 capture technology on performance and cost metrics. The approach fixes the natural gas feed rate for the power plant at the base plant feed rate for the specified combustion turbine model and modifies the corresponding capture case power plant, which closely matches the capture rate of the developmental technology, by removing its conventional CO_2 capture process and inserting the developmental CO_2 capture process in its place. By estimating the impact of the developmental CO_2 capture process auxiliary load, steam, and cooling water requirements on the overall NGCC power plant generating capacity, new performance values are generated, and the FEB case plant cost estimates are scaled to match the new design. Performance and cost metrics are calculated using the new estimated capacity and costs with the developmental CO_2 capture technology using standard NETL FEB calculations. [2, 4]

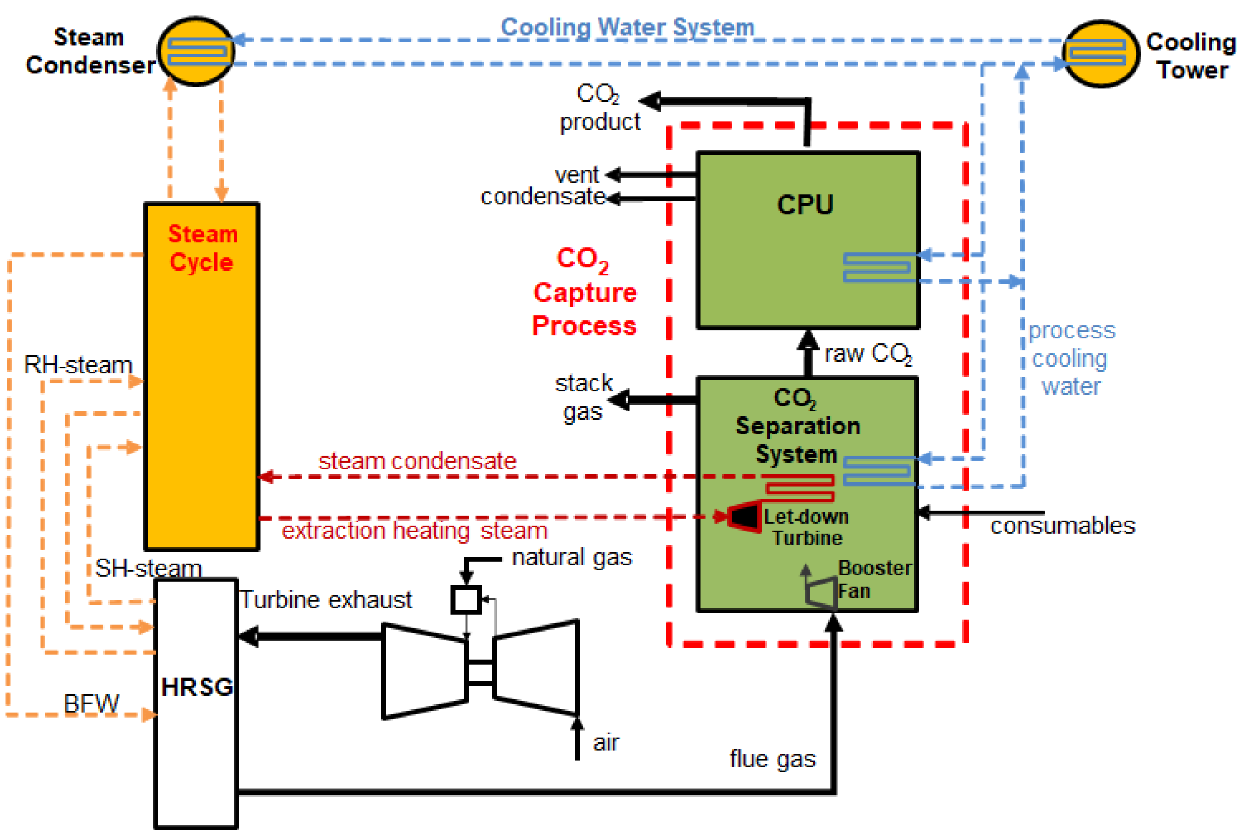
Section 4 discusses the NGCC methodology spreadsheet tool. Directions and examples are included within the tool and summarized in this section. The updated compression and purification tool, originally developed for PC plant post-combustion capture systems and added to the NGCC tool, is also discussed in this section.

2 CO_2 Capture Process Design and Cost Estimation Specification

The objective of this section is to provide an NGCC power plant framework and guidance for CO_2 separation technology developers to apply for conceptual evaluation of their technology's performance and cost. The boundary conditions for the major inlet and outlet streams, and the constraints for the functions of the CO_2 capture process systems are identified so that new, developmental CO_2 separation technologies can be properly developed and assessed on a common basis.

The post-combustion CO_2 capture process is an integrated process consisting of two systems in series, the CO_2 separation system and the CPU system as shown in Exhibit 2-1. The CO_2 separation system represents the post-combustion CO_2 separation technology of focus by developers. The required CPU system is dependent on the conditions and composition of the captured CO_2 stream exiting the separation technology. It can be a conventional compression and drying system or a more complex compression and purification system such as one based on partial condensation and distillation. [1, 3]

Exhibit 2-1. NGCC plant block flow diagram with developmental post-combustion CO_2 capture



Two base NGCC plant designs, Cases B31A and B32A, suitable for conventional post-combustion CO_2 capture systems are identified in this document. [2] Key conditions for the base plants are as follows:

- Two state-of-the-art (either 2017 F- or H-Frame) fully-loaded combustion turbine generators equipped with low NO_X burners, two heat recovery steam generators (HRSG) equipped with selective catalytic reduction, and one steam turbine generator in a multi-shaft 2×2×1 configuration
- Natural gas feed to at 93,272 kg/h (205,630 lb/h) for F-Frame or 124,025 kg/h (273,429 lb/h) for H-Frame
- Subcritical steam cycle with a single reheat 16.5 MPa/585°C/584°C (2,393 psia/1,085°F/1,084°F) for F-Frame cases and 18.5 MPa/585°C/562°C (2,683 psia/1,085°F/1,044°F) for H-Frame cases
- Total flue gas flow rate of 3,927 tonne/h (4,329 tph) for F-Frame or 5,233 tonne/h (5,769 tph) for H-Frame at a CO_2 composition of 4.08 mole percent for a CO_2 flow rate of 249 tonne/h (274 tph) for F-Frame or 331 tonne/h (365 tph) for H-Frame to the capture system
- No sulfur dioxide polishing step is required in the NGCC cases, as the pipeline natural gas sulfur content produces a flue gas with a sulfur dioxide content below the concentration in the outlet of the pre-scrubber used in the pulverized coal cases

The corresponding conventional capture cases have CO_2 capture rates of 90, 95, or 97 percent of CO_2 in the flue gas exiting the HRSG and fed to the capture system. These conventional CO_2 separation systems use amine absorber technology (Shell CANSOLV) and produce a raw CO_2 product that does not require purification other than dehydration. The CPU for the FEB capture cases included eight stages of conventional water inter-cooled CO_2 compression and a triethylene glycol (TEG) dehydration system. These conventional CO_2 separation systems are replaced with developmental CO_2 separation technology within the NGCC tool.

The plant cost estimates used within the NGCC tool are based on greenfield construction at a location in the Midwest. Additional design bases are described within the FEB. [2]

Integration between the base plant and the capture system is limited to the base plant providing flue gas, steam, power, and cooling water at baseline specifications and the capture system returning condensate and cooling water. The boundaries for the CO_2 capture process (as denoted by the red dashed line in Exhibit 2-1) and the interface steams are as follows:

- Flue gas stream entering the process
- Processed, CO_2-lean flue gas stream exiting the CO_2 separation system
- Sequestration-ready CO_2 product stream exiting the CPU [5]
- Inlet streams imported from the NGCC plant, such as extracted steam and cooling water
- Condensate streams and vent streams that exit the process

- Consumables entering or exiting the process (e.g., solvents, sorbents, catalysts, replacement materials, wastes for disposal)

Note: Additional equipment such as booster fans or let-down turbines needed to alter the flue gas or steam stream conditions for use by the technology are not included in the base plant design and must be included within the developing CO_2 capture process design.

The specifications for the boundary streams are listed in Exhibit 2-2.

Exhibit 2-2. Boundary stream specifications for the CO_2 capture process

Parameter	State-of-the-art 2017 F-Frame	State-of-the-art 2017 H-Frame
Case	B31A	B32A
Flue gas to CO_2 separation system	Temperature: 181°F	Temperature: 187°F
	Pressure: 14.8 psia	Pressure: 14.8 psia
	Total flow rate: 3,927 tonne/hr	Total flow rate: 5,233 tonne/hr
	CO_2 flow rate: 248.8 tonne/hr	CO_2 flow rate: 330.8 tonne/hr
	CO_2 composition: 4.08 mole %	CO_2 composition: 4.08 mole %
Flue gas out of CO_2 separation system (This applies if conventional compression and drying is used. If the separation system exit values differ, then further purification may be needed)	Temperature: 88°F	Temperature: 88°F
	Pressure: 24.8 psia	Pressure: 24.8 psia
	CO_2 composition: 97.8 mole %	CO_2 composition: 97.8 mole %
CO_2 product stream [5]	Delivery pressure: 2200 psig	Delivery pressure: 2200 psig
	Delivery temperature: 95°F	Delivery temperature: 95°F
	Minimum CO_2 content: 95 mole %	Minimum CO_2 content: 95 mole %
	Maximum O_2 content: 10 ppmv	Maximum O_2 content: 10 ppmv
Extraction steam conditions available for heating needs	IP turbine exhaust: 538°F, 73.5 psia	IP turbine exhaust: 549°F, 73.5 psia
	HP turbine exhaust: 672°F, 542 psia	HP turbine exhaust: 637°F, 525 psia
Cooling water conditions	60°F supply temperature	60°F supply temperature
	80°F return temperature	80°F return temperature

Within the NGCC tool, the technology developer selects the base plant design by specifying the combustion turbine model (F-Frame or H-Frame). The inlet stream flow, composition, and conditions of the feed to the capture system are fixed at the base plant case values. If inlet temperature and pressure requirements for the developmental capture system differ from the base plant values, equipment to modify those parameters must be included within the developer’s capture system design. The capture rate, capital and operation and maintenance (O&M) costs, auxiliary load, and cooling and steam requirements should be based on the developmental technology system and specified as inputs. The nature of the input parameters provided by the technology developer will set the basis for comparison (e.g., today's performance/cost, or future expected performance/cost versus today's Shell CANSOLV representation). The capture separation system CO_2 outlet content and conditions may vary somewhat from the baseline cases, as such, equipment costs and performance requirements should be included within the capture system estimates to meet the specified temperature, pressure, and composition (88°F, 24.8 psia, 97.8 mole% CO_2) of the reference FEB cases for inlet to a conventional compression and drying system. [2] Alternatively, the costs and performance for a user specified compression and purification system can be included if needed to meet the CO_2 product specifications for sequestration or enhanced oil recovery. [5] A simplified compression and purification calculator is included in the NGCC tool to provide high-level estimations that can be used as input if desired. Based on the specified capture rate, the greenfield plant design is assumed as comparable to one of the FEB baseline cases listed in Exhibit 2-3 with scaling of some accounts (steam cycle, cooling water, etc.) as needed to match technology inputs and generate metrics. Directions and examples are discussed in Section 4 and included within the NGCC tool. Additional data for these cases are included within the tool for guidance if needed.

Exhibit 2-3. Base plant data for methodology calculations

Base NGCC Plants from FEB [2]								
Case	State-of-the-art 2017 F-Frame				State-of-the-art 2017 H-Frame			
	B31A	B31B.90	B31B.95	B31B.97	B32A	B32B.90	B32B.95	B32B.97
CO_2 Capture Rate (%)	0	90	95	97	0	90	95	97
Capacity Factor (%)	85	85	85	85	85	85	85	85
Gross Power Output (MWe)	740	692	690	687	1,009	945	942	939
Auxiliary Power Requirement (MWe)	14	47	49	51	17	62	65	66
Net Power Output (MWe)	727	645	640	637	992	883	877	873
Natural Gas Flow Rate (lb/h)	205,630				273,429			
Net Plant HHV Efficiency (%)	53.6	47.6	47.3	47.0	55.1	49.0	48.7	48.8
Total Plant Cost ($million)	567	1,087	1,106	1,117	790	1,407	1,430	1,443
Total Overnight Cost ($million)	692	1,321	1,344	1,358	963	1,710	1,738	1,754
COE ($/MWh) (excluding T&S)	43.3	64.4	65.4	66.1	42.7	61.5	62.4	63.1
Capital Costs	9.9	21.3	21.8	22.1	10.1	20.1	20.6	20.9
Fixed Costs	3.6	7.4	7.6	7.7	3.5	6.8	7.0	7.1
Variable Costs	1.7	4.0	4.1	4.2	1.7	3.8	3.9	4.0
Fuel Costs	28.1	31.7	31.9	32.1	27.4	30.8	31.0	31.1
COE ($/MWh) (including T&S)	43.3	67.9	69.1	69.9	42.7	64.9	66.0	66.8
CO_2 T&S Costs	N/A	3.5	3.7	3.8	N/A	3.4	3.6	3.7
Cost of CO_2 Captured (excluding T&S), $/tonne	N/A	60.7	59.9	60.2	N/A	55.9	55.2	55.5
Cost of CO_2 Avoided (including T&S), $/tonne	N/A	80.8	79.8	80.4	N/A	75.0	74.2	74.8

Note: Costs of CO_2 captured and avoided are relative to the non-capture case for the same turbine model.

This NGCC methodology spreadsheet is a preliminary tool for comparison of greenfield plant baseline metrics using high-level data to allow for sensitivity and comparative analyses of developmental CO_2 capture technologies. More complex guidance/tools (including flexible operation impact issues/evaluation) are under development by NETL that are planned for use as technologies progress to later stages of development. Additional items to consider in estimating designs and costs for the developing CO_2 capture technologies that are not explicitly dealt with in the NGCC Tool include the following:

- Capture system footprint
- Operational summary for flexible operation
- Maintenance projections associated with flexible operation
- Design breakpoints associated with generation capacity
- Limits of the technology in terms of percent capture
- Whether the concept is focused on a given application or not
- Overall basis for the techno-economic analysis used to estimate cost and performance for processes with low technology readiness levels (TRL)

3 Plant Performance, Cost, and Metric Calculations

The objective of this section is to discuss the methodology for estimating the impact of a developmental CO_2 capture technology on performance and cost metrics. The approach fixes the natural gas feed rate for the power plant at the base plant feed rate for the specified fully loaded combustion turbine model and modifies the corresponding capture case plant at the specified capture rate by removing its conventional CO_2 capture process and inserting the developmental CO_2 capture process in its place. By selecting the capture case with the capture rate closest to the developmental technology capture rate, scaling uncertainties are minimized. The performance and costs for the base plant are factored and scaled to fit the new technology. The scaling calculations are based on the Quality Guidelines for Energy System Studies (QGESS): Capital Cost Scaling Methodology and performance factors described below. [6] Performance and cost metrics are calculated using the new estimated capacity and costs with the developmental CO_2 capture technology using standard NETL FEB calculations. [2, 4]

3.1 Performance Factoring

Developmental CO_2 capture technologies are expected to require steam extractions, cooling water, and auxiliary power at different rates than the FEB cases utilizing Shell CANSOLV capture systems even at the same capture rates. To address these differences, factors were developed to estimate the performance impacts.

The steam turbine generation is reduced from the non-capture design capacity by any steam extractions needed for the developmental CO_2 capture separation technology. These equations were originally developed for the steam turbines in the PC tool but are applicable to the NGCC tool as well. [1] Data for the potential steam extractions are listed in Exhibit 3-1. The technology developer must specify the steam extraction heating duty and temperature required, then the tool estimates the reduction in the stream turbine size. Two separate extraction streams can be specified within the NGCC tool.

Exhibit 3-1. Steam extraction data

Extracted Steam Source	Source Temperature (°F)/ Pressure (psia)	Max/Min Process Heating Temperature (°F)	Max/Min Plant Power Loss (kW/MMBtu heating duty)
IP-turbine exhaust	549/73.5	295/230	75.9/71.3
HP-turbine exhaust	672/711	496/318	138.6/111.5
HP-superheated steam	1100/3515	721/544	232.4/169.4

The data in Exhibit 3-1 and the following correlations are used for the extracted steam value impacts:

$$\text{Intermediate pressure (IP)-turbine exhaust: } V_{steam} = 8.9\text{ x}10\text{-}5 \bullet T^2 + 0.0252 \bullet T + 60.81$$

$$\text{High-pressure (HP)-turbine exhaust: } V_{steam} = 0.00026 \bullet T^2 - 0.0566 \bullet T + 103.37$$

$$\text{HP-superheated steam: } V_{steam} = 0.00093 \bullet T^2 - 0.7988 \bullet T + 331.71$$

Steam turbine power impact: $\Delta P_{Steam} = \Sigma \{ Q_H \bullet V_{steam} \}$

Where:

- V_{steam} – factor for impact on the turbine in (kW/MMBtu)
- T – stream heating temperature being achieved in the CO_2 separation process (°F)
- Q_H – extracted steam heating duty (MMBtu/hr) input by the developer
- ΔP_{Steam} – reduction in power generation from the base plant steam turbine value

As steam extraction increases, the condenser load decreases proportionally. This reduces the cooling water demand for the steam cycle. The final cooling water demand is estimated as the base plant cooling water flow minus the reduction in the condenser requirement plus the cooling requirements for the capture process and the compression and purification/drying process. The base plant cooling tower size is adjusted based on the estimated change in the cooling water demand. The auxiliary load required by the cooling tower is also adjusted proportionally to the cooling water demand change.

The net power capacity of the base plant design is modified by the change in steam turbine size estimated from the steam extractions as well as by the auxiliary load requirement input for the developmental CO_2 capture separation technology and the compression and purification/drying system and any changes in the cooling tower auxiliary load.

3.2 Cost Scaling

Since the base plants are set as the FEB cases, the modified equipment (steam cycle, condenser, cooling tower, etc.) is expected to remain within the scaling ranges defined in the QGESS. [6] The base plant values are the reference parameters and costs and the modified capture case including the developmental technology values are the scaled parameters and costs within the following equation that is used to scale capital costs:

$$SC = RC \bullet (SP/RP)^{Exp}$$

Where:

- Exp – exponent
- RC– reference cost
- RP – reference parameter
- SC – scaled cost
- SP – scaling parameter

Details for all scaling exponents and applicable ranges are included within the QGESS. [6] All parameters and exponents used within the NGCC tool are listed for each FEB case at the top of the calculations sheet in hidden rows, which the user can unhide to examine as needed. Additional information on applicable contingencies and owner's costs included within the total plant cost (TPC) estimates and total overnight costs (TOCs) is provided in the FEB report and NETL's cost estimation methodology QGESS. [2, 4]

3.3 NETL METRICS

The cost of electricity (COE), cost of CO_2 captured, and cost of CO_2 avoided are the primary metrics used by NETL to compare technologies. Since the plant costs within the NGCC tool are calculated using scaling from the FEB plant cases, the same metric equations used within the baseline studies can be used within the NGCC methodology.

The COE is the amount of revenue required per net MWh during the power plant's operational life to meet all capital and operational costs. The COE can be obtained from the following formula:

$$COE = [CCF * TOC + FO\&M + VO\&M + Fuel]/MWh$$

Where:

COE – cost of electricity, reported in $\$/MWh_{net}$
CCF – capital charge factor (0.773 fraction of capital per year for NGCC cases in FEB)
TOC – total overnight cost ($)
FO&M – fixed operating and maintenance cost ($/y)
VO&M – variable operating and maintenance cost at capacity factor ($/y)
Fuel – fuel cost at capacity factor ($/y)
MWh – annual net power generation at capacity factor (MWh_{net}/y)

The method used to determine capital charge factor and other estimating assumptions can be found in NETL's cost estimation methodology QGESS. [4] Within the FEB, the result of the above equation is presented as the real (i.e., constant dollar) levelized COE. [2] Due to the assumptions within NETL's cost estimating methodology defining real escalation as zero, the levelization factor equals 1.0 and the calculated value is a levelized value but also the first-year COE or a constant COE. To simplify calculations within the tool, detailed financial parameter calculations have been omitted, and this calculation result is defined as COE only. The technology developer can change the capital charge factor and add levelizing factors if desired to perform sensitivities on financial assumptions for all cases included the baseline study results.

The cost of CO_2 captured represents the minimum CO_2 plant gate sales price that will incentivize carbon capture relative to a defined reference non-capture plant. The cost of CO_2 captured is calculated using the following formula:

$$Cost\ of\ CO_2\ Captured\ \left(\frac{\$}{tonne}\right) = \frac{(COE_{CCS} - COE_{Non\ CCS})}{CO_2\ Captured}$$

The cost of CO_2 avoided represents the minimum CO_2 emissions price, when applied to both the capture and non-capture plant, that will incentivize carbon capture relative to a defined reference non-capture plant. The cost of CO_2 avoided is calculated using the following formula:

$$Cost\ of\ CO_2\ Avoided\ (\frac{\$}{tonne}) = \frac{(COE_{CCS\ with\ T\&S} - COE_{Non\ CCS})}{CO_2\ Emissions_{Non\ CCS} - CO_2\ Emissions_{CCS}}$$

Where:

CCS – capture plant for which the cost of CO_2 captured/avoided is being calculated (excluding T&S unless otherwise noted)
Non-CCS – reference non-capture plant, as described below
COE – cost of electricity, reported in $\$/MWh_{net}$
CO_2 Captured – rate of CO_2 captured, reported in $tonne/MWh_{net}$
CO_2 Emissions – rate of CO_2 emitted out the stack, reported in $tonne/MWh_{net}$

For a greenfield natural gas-based power system, the reference plant used to calculate the cost of CO_2 captured/avoided is the non-capture natural gas-based plant case for the selected turbine model (i.e., FEB Case B31A for a plant with F-Frame turbines or Case B32A for a plant with H-Frame turbines).

Within the NETL metrics, the capture plant cost estimates include CO_2 compression to 15.3 MPa (2,215 psia) for sequestration or use in enhanced oil recovery. [5] For the CO_2 emissions penalty, the COE value includes the cost of transport and storage (T&S), defined in the QGESS [7], as an additional O&M cost ($/y at capacity factor). For the cost of CO_2 captured, the additional cost is not included in the COE.

4 NGCC Methodology Spreadsheet Tool

The objective of this section is to discuss the NGCC tool that can be used for estimating the impact of a developmental CO_2 capture technology on performance and cost metrics. The developer selects the base plant by specifying the combustion turbine model to use as the basis for the calculations. The user also selects the capture rate for the corresponding FEB capture rate that most closely matches the developmental CO_2 capture technologies capture rate, which will be used for scaling. The tool calculates the NETL metrics for the modified plant with developmental technology using standard FEB calculations by removing the conventional CO_2 capture process and inserting the developmental CO_2 capture process in its place.

Inputs are presented in Exhibit 4-1. The values shown are examples only and not intended to represent actual technologies. Input values should be generated by the developer using boundary conditions and assumptions consistent with the design basis described in Section 2.

Exhibit 4-1. Developmental CO_2 technology NGCC tool inputs

Inputs		
Parameter	**Case T1**	**Case T2**
Developing CO_2 capture technology identifier	Example Technology 1	Example Technology 2
Capture rate of technology (% of CO_2 in flue gas)	92%	96%
Natural gas combustion turbine model selection (F-Frame or H-Frame)	F-Frame	H-Frame
NGCC base capture rate for scaling (% of CO_2 in flue gas)	90%	95%
NETL baseline case for comparisons	B31B.90	B32B.95
No. 1 extracted steam heating duty (MMBtu/h)	1,000	0
No. 1 extracted steam heating temperature (°F)	284	230
No. 2 extracted steam heating duty (MMBtu/h)	0	500
No. 2 extracted steam heating temperature (°F)	416	416
CO_2 separation/capture process cooling duty (MMBtu/h)	800	900
CO_2 compression and purification/drying cooling duty (MMBtu/h)	0	100
CO_2 separation/capture system power (kW)	10,900	15,000
CO_2 compression and purification/drying power (kW)	15,000	20,000
CO_2 loss rate (% of inlet flue gas CO_2)	0	0
CO_2 separation system cost ($1000) June 2018, TPC basis	350,000	600,000
CO_2 compression and purification/drying cost ($1000) June 2018, TPC basis	100,000	50,000
Key CO_2 capture process variable cost items	Makeup adsorbent	Membrane surface
Total CO_2 capture process variable cost ($1000/y)	5,000	8,000

Outputs are presented in Exhibit 4-2. The values shown are demonstrative examples only and not intended to represent actual technologies. Not all outputs are listed within this table. Intermediate values are also calculated and included within the spreadsheet.

Exhibit 4-2. Developmental CO_2 technology NGCC tool outputs

Inputs		
Parameter	**Case T1**	**Case T2**
Developing CO_2 capture technology identifier	Example Technology 1	Example Technology 2
Selected baseline case (for scaling and comparisons)	B31B.90	B32B.95
Plant power net (kW)	623,985	895,584
Plant higher heating value (HHV) efficiency (%)	46.1%	49.7%
CO_2 captured (tonne/h)	228.6	317.9
CO_2 emissions (tonne/h)	19.9	13.2
CO_2 capture rate (tonne/day)	5,487	7,630
TPC ($/kW)	1,656	1,665
TOC ($/kW$_{net}$)	2,013	2,023
TOC ($/tonne/day CO_2 captured)	228,851	237,412
COE without T&S ($/MWh$_{net}$)	63.8	61.4
COE with T&S ($/MWh$_{net}$)	67.5	64.9
Cost of CO_2 captured ($/tonne CO_2)	55.9	52.7
Cost of CO_2 avoided ($/tonne CO_2)	77.9	69.7
Plant net power reduction with respect to base plant (%)	3.24%	-2.08%
Plant efficiency reduction with respect to base plant (%)*	3.25%	-2.07%
Reduction in CO_2 captured (%)*	-2.22%	-1.05%
Reduction in CO_2 emissions (%)*	20.00%	20.00%
Reduction in TPC with respect to base plant (% $/kW)*	1.77%	-2.14%
Reduction in TOC with respect to base plant (% $/kW)*	1.77%	-2.14%
Reduction in COE without T&S with respect to base plant (%)*	0.90%	1.71%
Reduction in cost of CO_2 captured with respect to base plant (%)*	7.94%	4.45%
Reduction in cost of CO_2 avoided with respect to base plant (%)*	3.67%	5.95%

*Negative values indicate increases

Beyond this overall assessment information, this tool can be used for sensitivity analysis by varying any of the CO_2 capture process input parameters. It can be used to identify development needs for the CO_2 separation technology relating to its performance and cost and provides a quantitative measure of development progress achieved.

4.1 Directions for NGCC Tool

The nature of the input parameters provided by the technology developer will set the basis for comparison (e.g., today's performance/cost, or future expected performance/cost versus today's Shell CANSOLV representation) and determine the most effective way of using the tool. Multiple technologies or variations on a single technology can be entered in separate columns for comparisons. More cases can be added to the tool by inserting columns and copying the formulas from the existing columns to the new ones.

Specific directions for using the tool are included within the tool, but the general steps are as follows:

1. Enter developing CO_2 capture technology names or types, case designations, and design capture rates as percent of CO_2 in flue gas to be captured.
2. Select the NGCC base case combustion turbine model to be used as the base plant design.
3. Select the NGCC base case capture rate as percent of CO_2 in flue gas to be captured to be used for comparison and scaling. Select the rate that is closest to the design rate entered for each developing CO_2 capture technology.
4. Enter the input data for each developmental technology as shown in Exhibit 4-1. The first column contains example inputs from a reference case for illustration, and the next two are dummy examples that can be overwritten as needed.
5. Intermediate and final calculation results are listed within each column of the spreadsheet including the outputs shown in Exhibit 4-2.

The performance and design data for the FEB NGCC cases used in this tool are available to use as references within hidden rows at the top of the spreadsheet and can be un-hidden as needed. [2] The user should not modify these reference values unless there are specific reasons to do so such as examining changes or sensitivities to the original FEB assumptions.

4.2 Compression and Purification Tool

The CO_2 separation system captures CO_2 from the flue gas at the technology’s design rate. It also releases the captured CO_2 as a concentrated stream suitable for processing to the required CO_2 product specifications. Conventional post-combustion CO_2 separation systems, using amine-based solvents, and some developing post-combustion technologies produce raw CO_2 gas low in contaminants, generally requiring only gas dehydration and compression (i.e., conventional compression and drying system). In contrast, some developing CO_2 separation technologies result in raw CO_2 gas that requires compression as well as significant purification to separate contaminants and satisfy the CO_2 pipeline purity specifications. The CPU separates contaminants and inerts from the concentrated CO_2 stream to satisfy CO_2 product purity specifications and increases the CO_2 product pressure to the required pipeline pressure for transport to sequestration or use in enhanced oil recovery.

A CPU tool developed for the PC methodology determines if a conventional compression and drying (i.e., TEG dehydration) system can be used or if a more intensive purification process, based on low-temperature condensation of CO_2 with phase separation and distillation processing integrated with compression, is needed. [3] It provides quantitative performance and cost estimates that can be applied to support any CO_2 separation technology development effort. The tool was updated to match the assumptions and dollar year of the FEB cases for use with the NGCC methodology and incorporated into the NGCC tool as a separate sheet. [2] The developer can use this sheet to estimate the potential cost of a system to process the concentrated captured CO_2 stream exiting the developmental technology into the required CO_2 product. Detailed instructions are included within the tool. The block flow diagrams for the processes are shown in Exhibit 4-3 and Exhibit 4-4.

The steps for using the tool are as follows:

1. Enter data for the "Developing CO_2 Capture Technology Process Exit" stream requiring additional "CO_2 Purification &/or Compression and Dehydrations" in green cells.
2. Enter the inlet flue gas total flow rate in lbmole/hr.
3. Enter the inlet flue gas CO_2 concentration in mole fraction.
4. Enter the separation system CO_2 capture rate as percent of CO_2 in inlet flue gas.

   CO_2 Gas Flow From Separation System to CPU/Compression in lbmole/hr is calculated.
5. Enter the composition (CO_2, water, oxygen, nitrogen, and argon mole fractions) of the CO_2 rich exit stream from separation/capture technology.

The tool determines whether a conventional compression and drying system or conventional compression and purification system should be used and estimates the auxiliary power load, cooling water demand, CO_2 loss rate, and capital cost for the chosen CPU system. These values can be entered into the NGCC tool CALCULATIONS sheet for the CPU inputs if desired.

Exhibit 4-3. Conventional compression and drying system

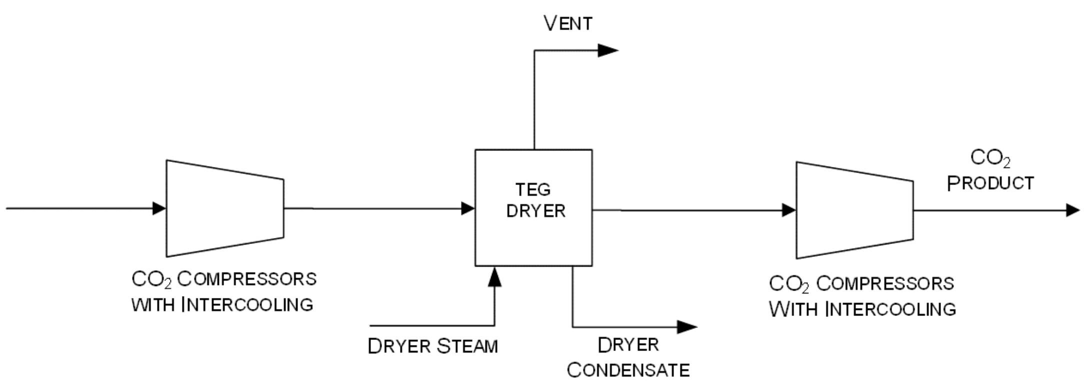
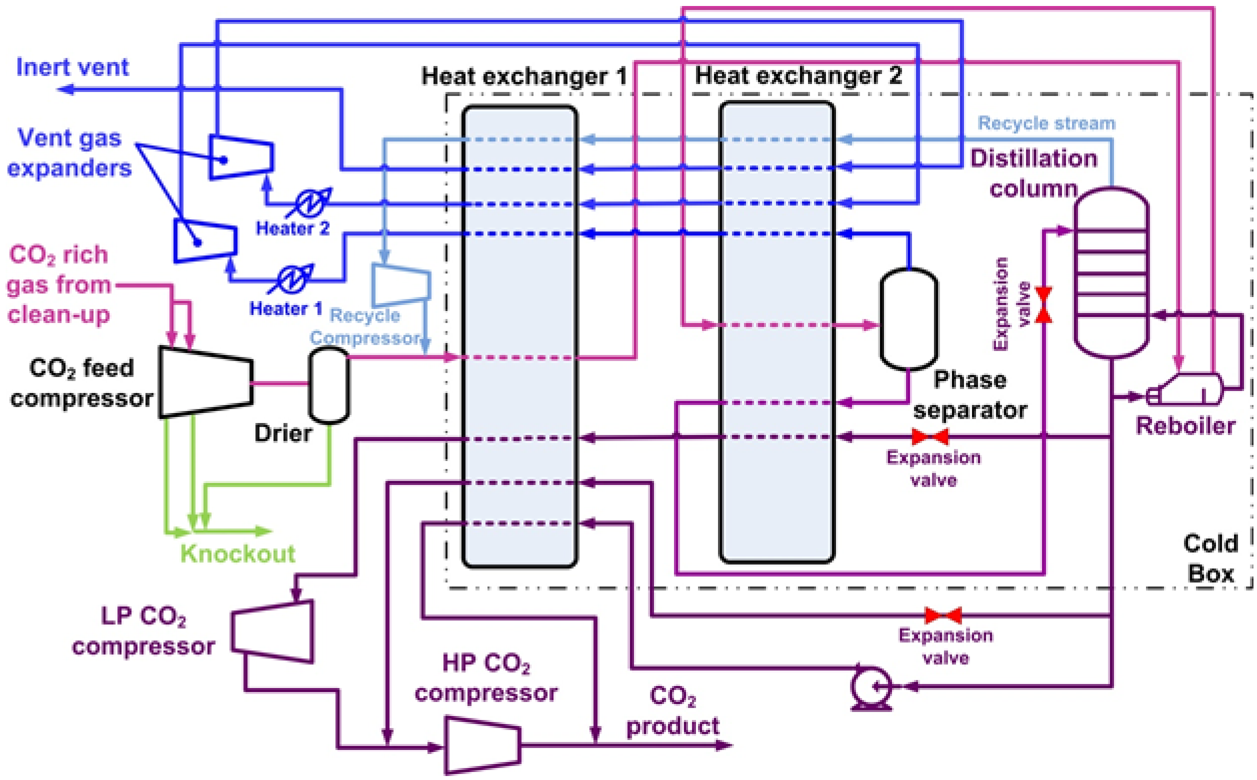


Exhibit 4-4. Conventional compression and purification system



4.3 What-If Examples

This NGCC methodology spreadsheet is a preliminary tool for comparison of greenfield plant baseline metrics using high-level data to allow for sensitivity and comparative analyses of developmental CO_2 capture technologies. The technology developer can use the tool to do What-If analyses by varying any of the inputs or assumed parameters. Two examples of how to do What-if analyses using Excel built-in functions are included within the tool and described below.

4.3.1 Goal Seek

Using Excel's Goal Seek feature is an option for determining what a developing technology input value needs to be to reach a specific goal. For example, if an analysis objective is to determine the capital cost value required to reduce the cost of CO_2 captured for developing CO_2 capture technologies to 10 percent below the cost of CO_2 captured for the base case, the following steps can be used:

1. Enter initial values for inputs of one or more developmental technologies then for each technology to be analyzed.
2. Select the What-If Analysis dropdown in the Data ribbon, then select Goal Seek.
3. Select the cell in the row labeled "Reduction in Cost of CO_2 Captured with respect to base plant (%)" as the SET CELL.

4. Enter 10% as the TO VALUE.
5. Select the cell in the row labeled "CO_2 Separation System cost ($1000: Cost Base June 2018, TPC basis)" as the BY CHANGING CELL, and click OK.
6. Excel will change the value until the reduction matches the value entered. Select OK when the solution is found then repeat for the remaining technologies as desired.

If any of the input values are interdependent, formulas can be entered for the input values to tie them together. The cell to be changed cannot contain a formula, but a factor cell can be included within a formula and then the factor cell selected as the BY CHANGING CELL.

In Exhibit 4-5, the values highlighted in yellow are the BY CHANGING CELLs and SET CELLs containing the results of following the steps above for three cases.

Exhibit 4-5. Goal seek example results

POST-COMBUSTION CO_2 CAPTURE TECHNOLOGY ASSESSMENT METHODOLOGY FOR NGCC POWER PLANTS			
BASE PLANT CO_2 CAPTURE PROCESS PERFORMANCE & COST INPUTS		Input Cells	Calculation Cells
Developing CO_2 Capture Technology Identifier	Base Case Example	Example Tech 1	Example Tech 2
Technology Case Identifier	FEB B31B.90	Case T1	Case T2
Enter Capture Percentage for Technology	90%	92%	96%
Select NGCC Base Turbine model	F-frame	F-frame	H-frame
Select NGCC Base Capture percentage for scaling and comparisons	90%	90%	95%
Selected Baseline Case (for scaling and comparisons)	B31B.90	B31B.90	B32B.95
Enter CO_2 Capture Process Performance Inputs (Inputs generated using prescribed design basis)			
No. 1 Extracted steam heating duty: Q_H (MMBtu/hr)	616	1,000	0
No. 1 Extracted steam heating temperature (F) (used to determine extraction point)	220	284	230
No. 2 Extracted steam heating duty: Q_H (MMBtu/hr)	5	0	500
No. 2 Extracted steam heating temperature (F) (used to determine extraction point)	416	416	416
CO_2 Capture Process cooling duty: Q_C (MMBtu/hr)	1,132	800	900
CO_2 CPU (compression+drying or CPU+compression) Process cooling duty: Q_C (MMBtu/hr)	118	0	100
CO_2 Separation System power: A_{SEP} (kW)	13,600	10,900	15,000
CO_2 CPU power: A_{CPU} (kW)	17,900	15,000	20,000
CO_2 Loss Rate (% of inlet flue gas CO_2)	0.0%	0.0%	0.0%
Enter CO_2 Capture Process Cost Inputs (Inputs generated using prescribed design basis)			
CO_2 Separation System cost ($1000: Cost Base June 2018, TPC basis)	351,850	334,317	543,688
CO_2 Compression and/or additional CPU cost ($1000; Cost Base June 2018, TPC basis)	61,329	100,000	50,000
Key CO_2 Capture Process variable cost items (for information only)	Makeup solvent	Makeup solvent	Membrane surface
CO_2 Capture Process variable cost: C_{VarCO_2} ($1000/yr **@ 100% Capacity Factor**, Cost Base June 2018)	11,928	5,000	8,000
MODIFIED BASE PLANT PERFORMANCE RESULTS			
CO_2 Capture Process CO_2 removal efficiency (%)	90.00%	92.00%	96.00%
Plant capacity factor: CF	85.00%	85.00%	85.00%
Natural Gas feed rate fixed at base plant [illegible]	[illegible]	[illegible]	273,429
Rows omitted for illustration			
CO_2 Emissions: (tonne/hr)	**24.9**	**19.9**	**13.2**
CO_2 Captured: (million tonne/yr @ capacity factor)	**1.7**	**1.7**	**2.4**
CO_2 Emissions: (million tonne/yr @ capacity factor)	**0.2**	**0.1**	**0.1**
MODIFIED BASE PLANT COST RESULTS			
Total overnight cost: TOC (1000$)	**1,237,397**	**1,235,340**	**1,742,807**
Total overnight cost: TOC ($/kW)	1,906	1,980	1,946
Total overnight cost: TOC ($/tonne/day CO_2 captured)	230,511	225,125	228,404
Cost of electricity: COE w/o T&S ($/MWh)	**62.2**	**63.4**	**60.3**
Cost of electricity: COE w T&S ($/MWh)	**65.6**	**67.0**	**63.8**
Cost of CO_2 Captured ($ per tonne CO_2)	**54.7**	**54.7**	**49.6**
Cost of CO_2 Avoided ($ per tonne CO_2)	**73.4**	**76.4**	**66.3**
ASSESSMENT WITH RESPECT TO NETL METRICS			
Plant Efficiency Reduction with respect to base plant (%)	**-0.66%**	**3.25%**	**-2.07%**
COE w/o T&S Reduction with respect to base plant: R (%)	**3.47%**	**1.61%**	**3.45%**
Reduction in Cost of CO_2 Captured with respect to base plant (%)	**10.00%**	**10.00%**	**10.00%**
Reduction in Cost of CO_2 Avoided with respect to base plant(%)	**9.27%**	**5.50%**	**10.54%**

4.3.2 Data Table

Using Excel's Data Table feature is an option for exploring sensitivities to developing technology input values. For example, if an analysis objective is to examine the impact of the total capital cost of the developmental technology on the cost of CO_2 captured for developing CO_2 capture, the following steps can be used:

1. Enter initial values for the developmental CO_2 technologies into columns.
2. Enter a 1 in a cell in an area where a data table can be added to be the factor cell initial value.

   Naming the cell to use as a factor or as the baseline value can make formulas easier to understand. In this example, the cell is named ExampleDTFactor.
3. Modify the input cell(s) in the calculations sheet rows for capital cost entries to be varied as needed (e.g., =ExampleDTFactor*#######).
4. Enter a column of values (e.g., as 0.5, 0.75, 1, 1.25, 1.5) to use as factor values to be examined in the area for the data table.
5. Enter formula(s) one row above and to the right of the column of values pointing to cell(s) containing the results to be analyzed for the cases of interest (e.g., the row labeled "Reduction in cost of CO_2 captured (%)").

   Additional data such as case names and formula result names can be added near the table to improve readability.
6. Select the rectangular range including the factor value column and the formula row.
7. Select the What-If Analysis dropdown in the Data ribbon, then select Data Table.
8. Select the factor value cell as the Column Input Cell and click OK.

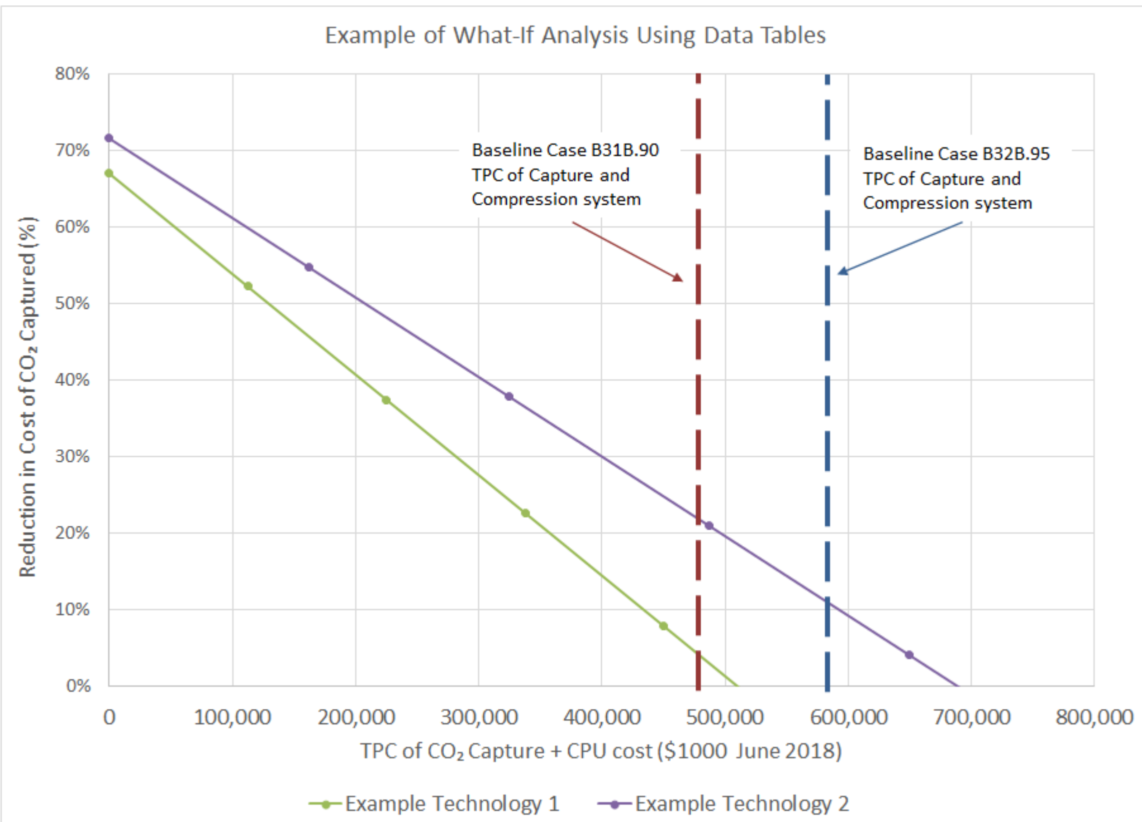
Excel will build a table of the formula row results based on the values in the column as shown in Exhibit 4-6. The resulting table of values can be used to generate charts like the one shown in Exhibit 4-7 for illustrating impacts in sensitivity studies.

The example above uses a factor approach, but data tables can be set up to change actual values within the spreadsheet. Data tables can also be set up for two variables with a single result formula. Columns and rows can not be inserted into data tables, so to expand the table, it must be deleted then redefined after the rows and/or columns are inserted. Accidentally clicking on the formula of the data table opens an error message, which can be exited by pressing the ESC key.

Exhibit 4-6. Data table example results

ExampleDTFactor:	1.00					
Case->	Base Case Example		Example Technology 1		Example Technology 2	
	TPC of CO_2 Capture + CPU cost ($1000 June 2018)	Reduction in Cost of CO_2 Captured with respect to base plant (%)	TPC of CO_2 Capture + CPU cost ($1000 June 2018)	Reduction in Cost of CO_2 Captured with respect to base plant (%)	TPC of CO_2 Capture + CPU cost ($1000 June 2018)	Reduction in Cost of CO_2 Captured with respect to base plant (%)
Factor Values	477,771	1.3%	450,000	7.9%	650,000.0	4.2%
0.00	0	65.5%	0	67.1%	0.0	71.6%
0.25	119,443	49.4%	112,500	52.3%	162,500.0	54.8%
0.50	238,886	33.4%	225,000	37.5%	325,000.0	37.9%
0.75	358,328	17.4%	337,500	22.7%	487,500.0	21.0%
1.00	477,771	1.3%	450,000	7.9%	650,000.0	4.2%
1.25	597,214	-14.7%	562,500	-6.8%	812,500.0	-12.7%
1.50	716,657	-30.8%	675,000	-21.6%	975,000.0	-29.6%
1.75	836,099	-46.8%	787,500	-36.4%	1,137,500.0	-46.5%
2.00	955,542	-62.8%	900,000	-51.2%	1,300,000.0	-63.3%

Exhibit 4-7. Data table example chart



Multiple developmental technology cases and What-If analyses can be combined within the NGCC tool making it a valuable tool that allows developers and evaluators to assess the status of developmental post-combustion CO_2 separation/capture technologies for NGCC power plants with respect to performance and cost metrics.

5 REFERENCES

[1] National Energy Technology Laboratory, "Methodology for Estimating PC Plant Capture Performance and Cost, DOE/NETL-2015/1731," U.S. Department of Energy, Pittsburgh, PA, 2015.

[2] National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 4a," U.S. Department of Energy, Pittsburgh, PA, October 2022.

[3] National Energy Technology Laboratory, "Development of Carbon Dioxide Purification Unit and Compression System Spreadsheet Tool," U.S. Department of Energy, Pittsburgh, PA, August 2015.

[4] National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance, NETL-PUB-22580," U.S. Department of Energy, Pittsburgh, PA, 2021.

[5] National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies: Carbon Dioxide Impurity Design Parameters," U.S. Department of Energy, Pittsburgh, PA, January 2019.

[6] National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology: Revision 4a Report," U.S. Department of Energy, Pittsburgh, PA, 2022.

[7] National Energy Technology Laboratory, "Quality Guidelines for Energy System Studies: Carbon Dioxide Transport and Storage Costs in NETL Studies," U.S. Department of Energy, Pittsburgh, PA, September 2019.

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