NATIONAL ENERGY TECHNOLOGY LABORATORY

DIRECT AIR CAPTURE CASE STUDIES: SORBENT SYSTEM

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July 8, 2022

DOE/NETL-2021/2865

Disclaimer

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Suggested Citation:
J. Valentine, A. Zoelle, "Direct Air Capture Case Studies: Sorbent System," National Energy Technology Laboratory, Pittsburgh, PA, July 8, 2022.

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TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

AACE	AACE International (formerly Association for the Advancement of Cost Engineering)
abs	Absolute
acfm	Actual cubic feet per minute
Ads t	Adsorption time
Ar	Argon
atm	Atmosphere (14.696 psi)
BBR4	Bituminous Baseline Revision 4
BEC	Bare erected cost
BFD	Block flow diagram
BFW	Boiler feedwater
BOP	Balance of plant
Btu	British thermal unit
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	*n*-Butane
CAPEX	Capital expenses
CC	Capital charges
CF	Capacity factor
CH_4	Methane
CH_4S	Methanethiol
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
COC	Cost of CO_2 capture
COE	Cost of electricity
CPU	CO_2 purification and compression unit
Cr	Chromium
CS	Carbon steel
CT	Combustion turbine
CTG	Combustion turbine generator
CWT	Cold water temperature
DAC	Direct air capture
DCS	Distributed control system
Des t	Desorption time
DOE	Department of Energy
ELG	Effluent limitation guidelines
Eng'g CM H.O.& Fee	Engineering construction management, home office and fees
F_{CO2}	Annual flow of CO_2 from the DAC plant
FCR	Fixed charge rate
FECM	Office of Fossil Energy and Carbon Management
FP	Fuel cost
ft	Foot
ft^3	Cubic foot
FW	Feedwater
g	Grams
gal	Gallon
GJ	Gigajoule
g-mol	Gram moles
gpm	Gallons per minute
Gt	Gigatonne
h, hr	Hour
H_2O	Water
H_2S	Hydrogen sulfide
HCl	Hydrogen chloride
Hg	Mercury
HHV	Higher heating value
HRSG	Heat recovery steam generator
HVAC	Heating, ventilation, and air conditioning
HWT	Hot water temperature
Hz	Hertz
in	Inch
in. H_2O	Inches of water
IOU	Investor-owned utility
IP	Intermediate pressure
ISO	International Organization for Standardization
K	Kelvin
K_2CO_3	Potassium carbonate
kg	Kilogram
kg-mol	Kilogram mole
kJ	Kilojoule
km	Kilometer
kPa	Kilo pascal
kV	Kilovolt
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
kWt	Kilowatt thermal

lb	Pound
lb-mol	Pound-mole
LCOE	Levelized cost of electricity
LHV	Lower heating value
LNB	Low-NOx burner
LP	Low pressure
lpm	Liters per minute
m	Meter
M/MM	Million
m^3	Cubic meter
Mg	Magnesium
min	Minute
MOF	Metal organic framework
mol	Mole
MPa	Megapascal
Mt	Million tonnes
MVA	Megavolt-ampere
MW, MWe	Megawatt electric
MWh	Megawatt-hour
N/A	Not applicable/available
N_2	Nitrogen
NaOH	Sodium hydroxide
NAS	National Academies of Sciences, Engineering, and Medicine
NETL	National Energy Technology Laboratory
NGCC	Natural gas combined cycle
No.	Number
NOAK	N^{th} of a kind
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
OC_{FIX}	First-year-of-operation fixed annual operating costs
OC_{VAR}	First-year-of-operation variable annual operating costs
O-H	Overhead
OM	O&M costs
OPEX	Operating expenses
p.f.	Power factor
Pa	Pascal
Pdrop	Pressure drop
PEI	Polyethylenimine
ph	Phase
PM	Particulate matter
ppm	Parts per million
ppmv	Parts per million, volume
ppmvd	Parts per million, volume dry
psi	Pounds per square inch
psia	Pound per square inch absolute
psig	Pound per square inch gauge
QGESS	Quality Guidelines for Energy System Studies
R&D	Research and development
RO	Reverse osmosis
s	Second
scf	Standard cubic feet
scfm	Standard cubic feet per minute
scm	Standard cubic meter
SCR	Selective catalytic reduction
SO_2	Sulfur dioxide
SS	Stainless steel
ST	Steam turbine
STG	Steam turbine generator
T&S	Transport and storage
TASC	Total as-spent capital
t CO_2	Tonnes CO_2
TEG	Triethylene glycol
TOC	Total overnight cost
ton	U.S. short ton
tonne	Metric ton (1,000 kg)
TPC	Total plant cost
TRI-PE-MCM-41	Triamine-grafted, pore-expanded MCM-41 mesoporous silica
U.S.	United States
U	Superficial velocity
V	Volt
V-L	Vapor-liquids
WG	Water (gauge)
wt%	Weight percent
y, yr	Year
Y_2O_3	Yttrium oxide
°C	Degrees Celsius
°F	Degrees Fahrenheit

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EXECUTIVE SUMMARY

In 2018, the National Academies of Sciences, Engineering, and Medicine (NAS) released the report "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda." The report focuses on technologies that remove CO_2 from the atmosphere, so that it may be stored or utilized. The report assesses five separate carbon dioxide removal technologies, including direct air capture (DAC), and provides perspective on the state of these technologies. Several of the DAC technology developers highlighted in the NAS report have projected that the cost of removing CO_2 from the atmosphere will rapidly fall in the next few years. Estimates on the cost to remove CO_2 from the atmosphere disclosed by various sorbent and solvent technology developers roughly span $95–600/tonne, with a stated goal to reduce costs below $100/tonne by 2030. [1] [2] [3]

The objective of this study is to develop an independent assessment of the performance and cost of a generic sorbent-based DAC system. The sorbent considered is not reflective of any one material type, or functionalization approach; rather, it represents an approximate average of reported material performance in the literature. The system configuration represents what was judged to be the most reasonable configuration if these systems were to be deployed in the near term. Capital and operating cost estimates for DAC specific accounts were developed based on commercially proven technology from reputable suppliers by Black & Veatch using their in-house cost estimating references. Since there is limited public information for industrial-scale DAC systems, sensitivity analysis was conducted on multiple process and cost parameters.

As a starting point for this study, a packed bed system was evaluated as a first pass to assess material performance. Due to the pressure drop limitations of the packed bed configuration, a monolith-supported sorbent configuration was also evaluated. The packed bed cases, Case 0 and Case 0-EB are presented in the appendices of this report for context and completeness, while Case 0B and Case 0B-EB, both of which assume a monolith sorbent support are highlighted. Exhibit ES-1 summarizes the cases presented in this report.

Exhibit ES-1. Case matrix

Case	Sorbent Configuration	Power Source	CO_2 Captured from Power Source, %	Power Source Capture Technology
0	Packed bed	NGCC	90	Shell's Cansolv
0-EB		Carbon free electricity	N/A	N/A
0B	Monolith	NGCC	90	Shell's Cansolv
0B-EB		Carbon free electricity	N/A	N/A

The Case 0B DAC plant considers a combustion turbine that produces electricity to support plant auxiliary load; a heat recovery steam generator (HRSG) to generate steam for all plant thermal requirements, as well as excess steam for power production in a small Rankine bottoming cycle; Shell's Cansolv system for capturing 90 percent of the CO_2 present in the combustion turbine flue gas; a CO_2 compressor dedicated to compressing only the CO_2 product from the Cansolv system; air fans that pressurize and deliver inlet air to monolith DAC absorbers; 20 (60-foot diameter) DAC adsorber vessels to remove CO_2 from the inlet air with subsequent thermal regeneration producing a CO_2 product stream; and a dedicated CO_2 compressor for compressing only the DAC CO_2 product. The DAC system was sized to meet the 2018 minimum 45Q tax credit threshold: 100,000 tonnes CO_2/yr (110,230 tons/yr). [4] To achieve a net atmospheric CO_2 reduction of 100,000 tonnes/yr, it is necessary to remove 113,900 tonnes/yr (125,550 tons/yr) in the DAC absorbers and an additional 125,090 tonnes/yr (137,890 tons/yr) from the natural gas combined cycle (NGCC) flue gas. The additional 13,900 tonnes/yr (15,320 tons/yr) removed in the DAC adsorbers accounts for the 10 percent of CO_2 not captured by the Cansolv process from the NGCC flue gas.

An additional case, Case 0B-EB, considers the same DAC system approach as Case 0B (i.e., air fans that pressurize and deliver air to the monolith adsorber vessels, and dedicated DAC CO_2 compression), with the exception of the power and steam generation sub-systems. To represent a sorbent-based DAC system in which energy requirements (electrical and thermal) could be completely satisfied by renewable or low carbon energy sources, Case 0B-EB utilizes an electric boiler to produce the steam needed for thermal regeneration of the CO_2 sorbent. For the base Case 0B-EB, it is assumed that the electricity required to satisfy the auxiliary load is purchased at a sale price of $60/MWh. The emission profile, or carbon footprint, of the purchased electricity is not considered in this analysis as only emissions within the plant bounds are quantified. However, it is reasoned that the electricity required for this scenario will need to be low carbon to facilitate a truly negative-emissions system and will likely be provided by renewable sources. In order to gauge the impact of different renewable electricity sources, sensitivities were conducted on capacity factor and the sale price of purchased electricity. As stated, it is assumed that purchased electricity has no associated process CO_2 emissions, such that the gross capture rate of the Case 0B-EB DAC system, at 100,000 tonnes CO_2/yr (110,230 tons/yr), is equal to the net capture rate.

Capital cost estimates for DAC systems, Case 0 and Case 0-EB, were developed by Black & Veatch, with an uncertainty range of +/- 50 percent, consistent with Association for the Advancement of Cost Engineering (AACE) Class 5 cost estimates (i.e., concept screening), based on the level of engineering design performed. In all cases, this report relies on vendor cost estimates for component technologies and process equipment, corresponding to the assumption- and/or model-derived equipment specifications. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs, which can be a challenge for emerging technologies. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required. All costs are reported in 2019 dollars.

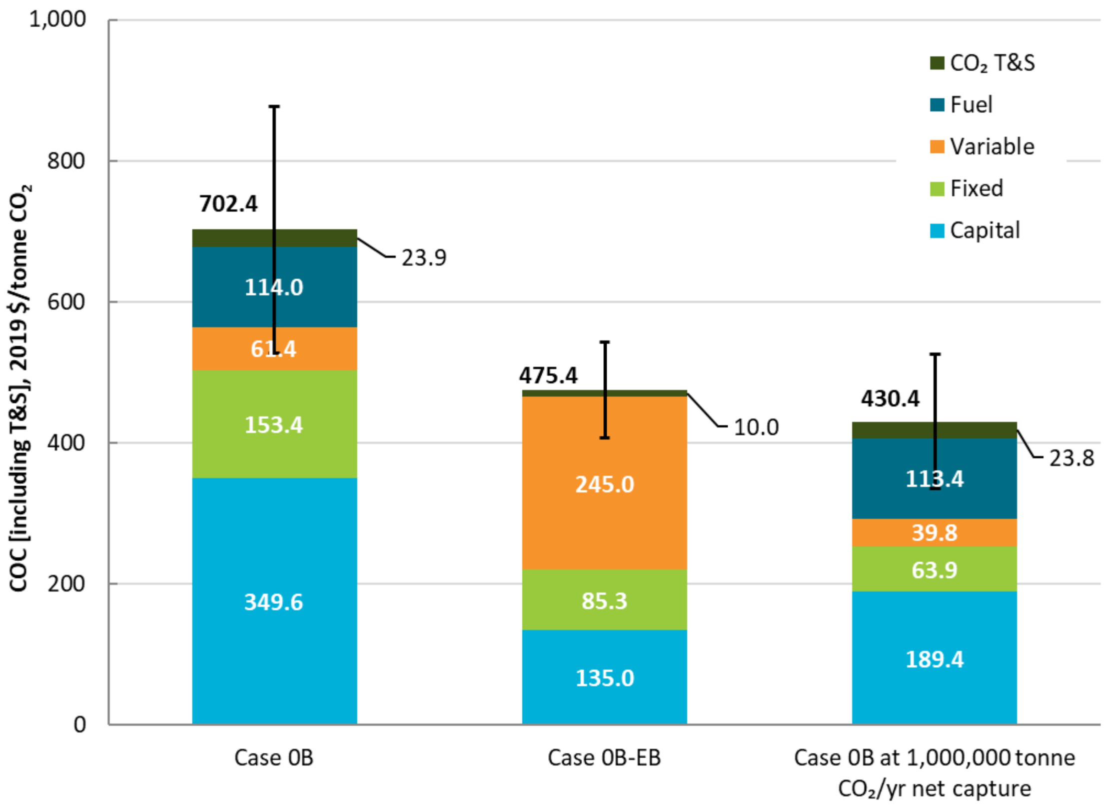
Sorbent-based direct air capture (DAC) systems are an immature technology, lacking a history of commercial deployment at scale. The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher the presented estimates. Absent demonstrated first-of-a-kind (FOAK) plant costs associated with a specific plant configuration/technology, it is difficult to explicitly project fully mature, N^{th}-of-a-kind (NOAK) values. Consequently, the cost estimates provided herein represent neither FOAK nor NOAK costs. Nevertheless, the application of a consistent methodology - and the presentation of detailed equipment specifications and costs based on contemporary sources - facilitate comparison between cases as well as sensitivity analyses to guide R&D, and generally improve upon many publicly available estimates characterized by more opaque methods and sources, and less detail.

Anticipated actual costs for projects based upon any of the cases presented herein 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 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.

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 here.

Case 0 and Case 0-EB are analogous to Case 0B and Case 0B-EB, respectively; these cases consider the same DAC system approach except for the sorbent structure and sorbent properties. Unlike the monolith adsorbers assumed in Case 0B and Case 0B-EB, Case 0 and Case 0-EB assume packed bed absorbers. Capital costs for Case 0B and Case 0B-EB were scaled from the Case 0 and Case 0-EB capital cost estimates. Using the methodology described in this study, the cost of CO_2 capture (COC) for Case 0B is $702/tonne ($637/ton) and $475/tonne ($431/ton) for Case 0B-EB; a breakdown of these costs is shown in Exhibit ES-2. All costs are reported on a 2019-dollar basis. Exhibit ES-2 also presents the cost of Case 0B scaled-up to a 1 M tonnes CO_2 removed/yr net capacity to highlight the impacts of plant scale. Increasing the plant capacity from 100,000 tonnes CO_2/yr-net to 1 M tonnes CO_2/yr-net reduces the COC by 39 percent, from $702/tonne ($637/ton) to $430/tonne ($390/ton).

Exhibit ES-2. Cost of CO_2 capture on a net CO_2 removed basis for Case 0B, Case 0B-EB, and Case 0B at 1 M tonne CO_2/yr-net scale



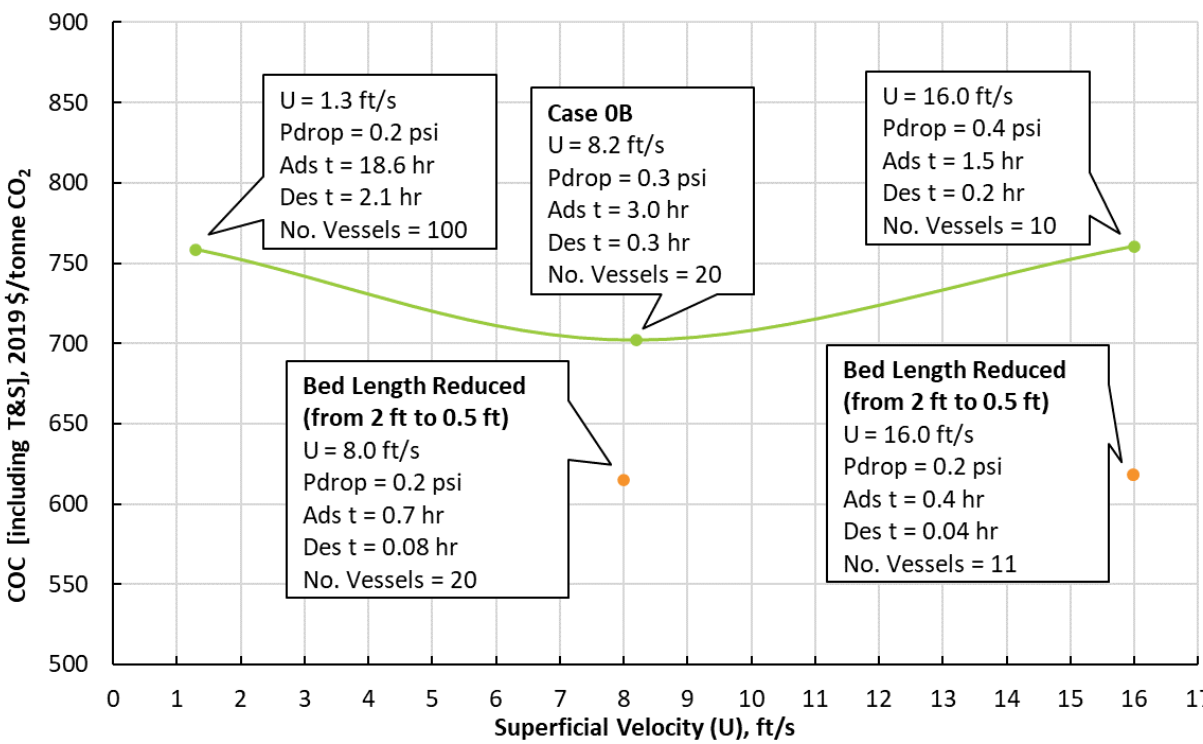
Note: Case 0B-EB assumes that the auxiliary load is satisfied by purchased electricity at a price of $60/MWh. Additionally, for purposes of sizing the plant, it assumes that the purchased electricity has no associated process CO_2 emissions.

The COC is reported on a net CO_2 removal basis. In other words, this price is based on the 100,000 tonnes CO_2/yr (110,230 tons/yr) net removed from the atmosphere. The numerator includes the costs for the DAC process and supporting systems, while the denominator reflects the net CO_2 removal of 100,000 tonnes. The error bars included in Exhibit ES-2 represent the potential COC range relative to the maximum and minimum capital cost uncertainty ranges detailed earlier. The COC ranges presented are not reflective of other changes, such as variation in fuel price, operation and maintenance (O&M) labor price, capacity factor, etc. Note that many cost and performance assumptions made for Case 0B and Case 0B-EB are fairly optimistic and could result in a best-case COC.

In recent years, there has been a significant increase in research focused on DAC. Some developers have advanced to small pilot-scale testing of their processes and published performance and cost estimates for broad scientific review. Other developers, however, have released only limited public information regarding their processes. For example, Climeworks has stated publicly that they constructed and are currently operating 15 DAC plants in Europe, but the level of detail publicly available data for these plants appears to be lacking. [4] Future changes in regulations, the implementation of additional tax incentives related to CO_2, shifts in public opinion related to carbon-based fuels and CO_2 in the atmosphere, and many other factors may create an environment where DAC technologies are economically competitive or legislatively mandated. Research and development of DAC technologies should continue to investigate new materials with properties favorable for DAC, refine existing process configurations to minimize pressure drop and auxiliary load, and pursue new process concepts with a focus on capital cost reduction.

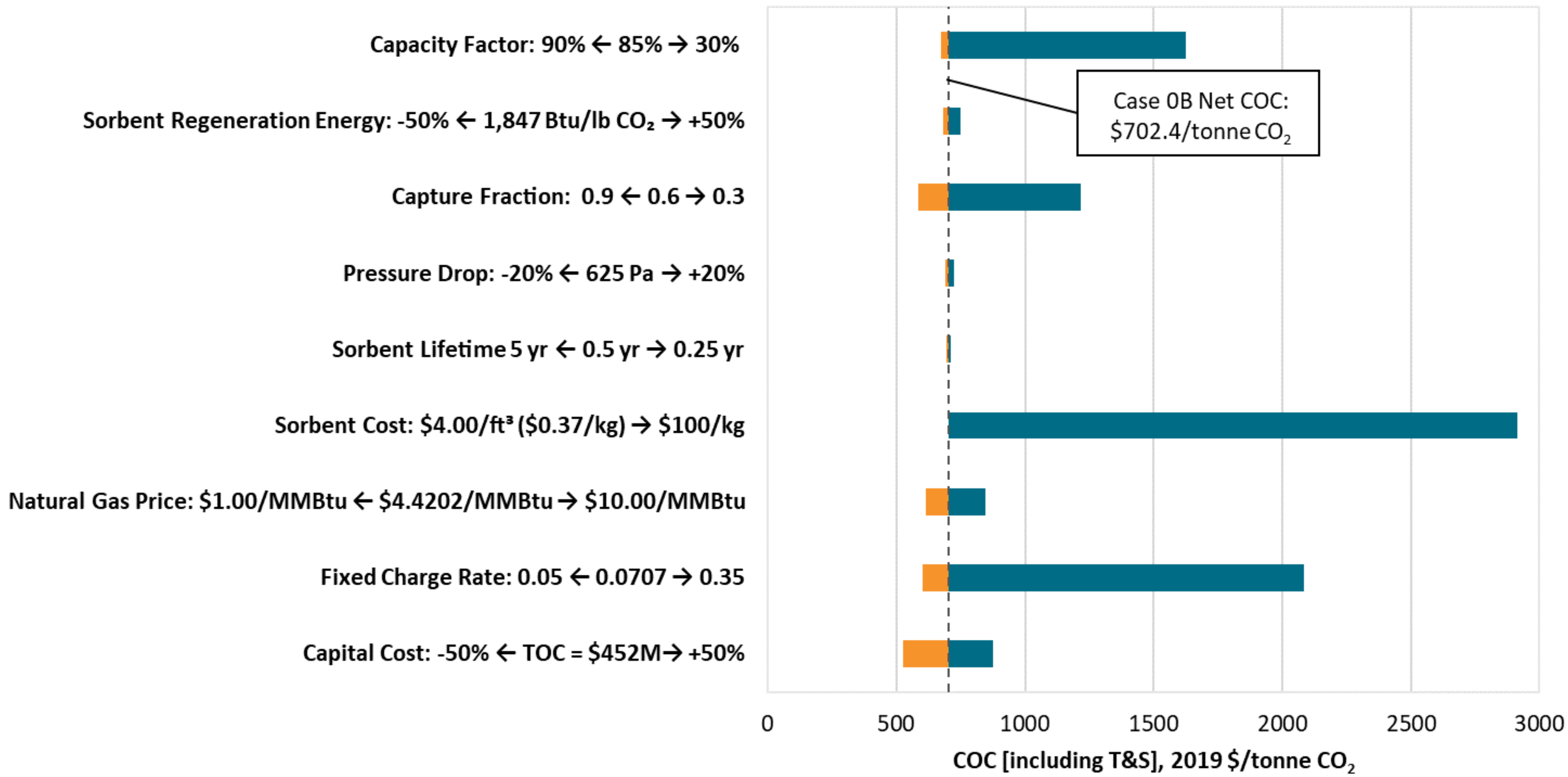
Several references present test results for different materials that could have future application for DAC, but much of this work is performed at bench scale. Moreover, there is limited public information on the system configurations that would be pursued, as much of the material performance testing results are obtained with bench-scale test set-ups. As new and improved low pressure drop sorbent support materials for DAC applications continue to be reported in the literature, it is expected that the base assumptions for Case 0B will be exceeded resulting in further reductions in the overall COC. A sensitivity analysis evaluating the influence of higher superficial velocities and shallower bed depths on Case 0B was performed; results are plotted in Exhibit ES-3.

Exhibit ES-3. Sensitivity of Case 0B to superficial velocity and bed depth



A sensitivity analysis was also conducted on multiple other process parameters and cost parameters to gauge the impact of changing parameters on the Case 0B system performance and COC. The parameters of interest include capital cost, natural gas price, sorbent cost, sorbent lifetime, financing assumptions (fixed charge rate), system pressure drop, system capture fraction, sorbent regeneration energy, and a single case addressing CO_2 product purity from the adsorber vessels. A summary of the sensitivity results is shown in Exhibit ES-4.

Exhibit ES-4. Summary of Case 0B COC sensitivity results



Results of the individual sensitivity case assessing CO_2 product purity (requiring a CO_2 purification unit) showed small changes to the COC (less than 4 percent increase). Of the sensitivity studies shown in Exhibit ES-4, sorbent cost has the greatest impact on COC. The base case cost \$4.0/ft^3 (\$0.20/kg) was recommended by Black & Veatch to reflect a generic cost for NOAK sorbents used commercially. The sensitivity range evaluates the impact of higher sorbent cost (up to \$100/kg) reported in literature.

Of the evaluated performance parameters, capture fraction (the fraction of CO_2 captured from the inlet air by the adsorber vessel sorbent before the air discharges to atmosphere) has the greatest potential to reduce COC. Fixed charge rate appears to have the potential to significantly increase the COC, but as will be discussed in later sections, the financial parameters that would be most realistic for the DAC process are unknown, given the current state of the technology, risks associated with deployment, regulatory drivers impacting CO_2 emissions, presence of a robust CO_2 market, and other factors. Therefore, the maximum sensitivity point investigated could be unrealistic. None of the sensitivity results applied to the 100,000 tonne/yr scale were able to independently reduce the Case 0B COC below \$500/tonne CO_2. However, a consolidated sensitivity case could break the \$500/tonne CO_2 threshold at the 100,000 tonne/yr scale.

1 Introduction

In 2018, the National Academies of Sciences, Engineering and Medicine (NAS) released the report "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda." The report focuses on technologies that remove CO_2 from the atmosphere, so that it may be stored or utilized. The report assesses five separate carbon dioxide removal (CDR) technologies, including direct air capture (DAC), and provides perspective on the state of these technologies. The report also makes research and development (R&D) recommendations in an effort to push advancement of technologies and drive down the cost of deployment.

Technology developers have projected that the cost of removing CO_2 from the atmosphere will rapidly fall in the next few years. Climeworks, whose technology applies an amine-functionalized filter, stated in 2019 that the cost to remove CO_2 from the atmosphere using their technology is roughly $600/tonne, and they project that cost to drop to $200/tonne in the next three to four years, with a long-term goal of less than $100/tonne by 2030. [1] Carbon Engineering, who apply a solvent technology to remove CO_2 from the atmosphere, published a techno-economic analysis in 2018 that projects a cost to remove CO_2 of $94–232/tonne, depending on financial considerations, regional energy costs, and other factors. [2]

R&D efforts focused on reducing cost have increased in recent years, [5] with pilot facilities and test plants aiming to demonstrate technology feasibility while providing an opportunity to optimize plant operation. Climeworks constructed and currently operates 15 DAC plants in Europe and has demonstrated their technology at 4,000 tonnes/yr scale. [6] Another developer, Global Thermostat, who utilizes an amine-modified monolith, demonstrated their technology using a 1,000 tonnes/yr pilot. [7]

The objective of this National Energy Technology Laboratory (NETL) study is to develop an independent assessment of the performance and cost of a generic sorbent-based DAC system. The sorbent considered is not reflective of any one material type, or functionalization approach; rather, it represents an approximate average of reported material performance in the literature. The system configuration, which will be discussed in further detail in later sections, represents what was judged to be the most reasonable configuration if these systems were to be deployed in the near term. Capital and operating cost estimates for DAC specific accounts were developed based on commercially proven technology from reputable suppliers by Black & Veatch using their in-house cost estimating references. The capital cost estimates represent an AACE International (AACE) Class 5 estimate, with an uncertainty range of +/- 50 percent. Since there is limited public information for industrial-scale DAC systems, sensitivity analysis was conducted on multiple process and cost parameters.

2 Literature Review

The literature review for DAC sorbent systems includes two parts: a review of the NAS report's techno-economic analysis of a sorbent DAC system, and a general review of the scientific literature on sorbent DAC.

2.1 National Academy of Sciences Report

NAS developed and published a research agenda for CDR technologies. [7] The report aimed to identify the research needs required to commercialize these technologies and to assess the benefits, risks, and scale potential for atmospheric CDR and storage approaches. The report included an evaluation of six technologies: coastal blue carbon, terrestrial carbon removal and storage, bioenergy with carbon capture and storage, carbon mineralization, geologic storage, and DAC. Both sorbent-based and solvent-based DAC technologies were included in the NAS report, sorbent-based technologies are highlighted in this report.

NAS presented a performance and cost analysis for a generic sorbent process. The analysis assumptions used by NAS are listed below; additional assumptions are presented in Exhibit 2-1:

- Emissions from heat and energy sources are considered, but embodied emissions of equipment are not
- Cost and performance results do not include compression, transportation, injection, and storage
- Heat integration was not evaluated

Exhibit 2-1. NAS analysis assumptions

Parameter	Value
Plant capture rate from air	1 Mt/yr CO_2
CO_2 concentration in air	400 ppmv
Volumetric flow rate of air	≥ 58,000 m^3/s
Capture fraction from air	≥ 60% CO_2
Concentration of product	≥ 98 percent CO_2
Plant life	10 years
Assumed Emission Factors	**(g CO_2/kWh)**
Heat from natural gas	227
Heat from coal	334
Heat from nuclear	4
Heat from solar	8.3
Electricity from grid (U.S. average)	743
Electricity from natural gas	450
Electricity from coal	950
Electricity from nuclear	12
Electricity from solar	25
Electricity from wind	11

NAS evaluated performance and costs for a range of DAC system model parameters. Best and worst cases were developed to represent the most optimistic and most pessimistic parameter values for all parameters. Three average (realistic) cases were developed using mid-range parameter values. NAS-assumed process parameters are presented in Exhibit 2-2; estimated energy requirements are presented in Exhibit 2-3. [7]

Exhibit 2-2. NAS-assumed DAC system process parameters

Parameter	Assumed Values
Inputs	
Contactor to adsorbent ratio, kg/kg	0.1–4.0
Sorbent total capacity (at 400 ppm), mol/kg	0.5–1.5
Desorption swing capacity, mol/mol	0.75–0.90
Desorption pressure (vacuum swing adsorption), bar	0.2–1.0
Desorption final temperature (temperature swing adsorption), K	340–373
Heat of adsorption (CO_2), kJ/mol	40–90
Adsorbent lifetime, years	0.25–5.0
Adsorbent purchase cost, $/kg	15–100
Air velocity, m/s	1–5
Outputs	
Adsorption time, min	8–50
Desorption time, min	7–35
Mass transfer coefficient	0.01–0.1
Pressure drop, Pa	300–1,400

Exhibit 2-3. NAS-assumed DAC thermal and electric requirements

Unit Operation	Type	Energy Requirement (GJ/t CO_2)
Desorption heat[A]	Thermal	3.4–4.8
Contactor fans	Electrical	0.55–1.12
Desorption vacuum pump	Electrical	0.011–0.014
	Total	**3.95–5.92**

[A]Assumes 100°C (212°F) saturated steam

For the generic sorbent system, NAS reported simplified equipment lists, capital costs, operating costs, and the total cost of capture in $/tonne CO_2; however, costs and financial assumptions were not detailed. Capital and operating costs associated with each piece of equipment are provided in Exhibit 2-4. [7] The source of capital cost information is not clear. Overall results from the NAS study are presented in Exhibit 2-5. [7]

Exhibit 2-4. NAS generic sorbent-based DAC system capital and operating costs

Capital Costs	Cost ($/t CO_2)
Adsorbent	70–186
Blower	2.1–6.7
Vacuum pump	2.6–8.5
Condenser	0.07–0.1
Contactor	1.3–4.1
CAPEX Subtotal	**76–205**
Operating Costs	**Cost ($/t CO_2)**
Adsorption	9–19
Steam	2.2–3
Vacuum pump	0.2–2.4
OPEX Subtotal	**11–24**
Total Cost of Capture	**88–228**

Exhibit 2-5. NAS DAC system performance and cost results summary

<table>
<tr><th>DAC Type</th><th>Electric/ Thermal Energy Source</th><th>Electric Requirements (GJ/tonne CO_2)</th><th>Thermal Requirements (GJ/tonne CO_2)</th><th>Capture Costs ($/tonne CO_2)</th><th>Net CO_2 Removed (Mt/yr)</th><th>Net CO_2 Removed Costs ($/tonne CO_2)</th></tr>
<tr><td rowspan="6">Generic Solid Sorbent</td><td>Solar/solar</td><td rowspan="6">0.55–1.1</td><td rowspan="6">3.4–4.8</td><td>88–228</td><td>0.892–0.992</td><td>89–256</td></tr>
<tr><td>Nuclear/ nuclear</td><td>88–228</td><td>0.91–0.994</td><td>89–250</td></tr>
<tr><td>Solar/ natural gas</td><td>88–228</td><td>0.70–0.78</td><td>113–326</td></tr>
<tr><td>Wind/ natural gas</td><td>88–228</td><td>0.70–0.78</td><td>113–326</td></tr>
<tr><td>Natural gas/ natural gas</td><td>88–228</td><td>0.56–0.71</td><td>124–407</td></tr>
<tr><td>Coal/coal</td><td>88–228</td><td>0.26–0.53</td><td>166–877</td></tr>
</table>

Although NAS evaluated multiple energy sources for thermal energy and electric requirements, the operating costs associated with each type of generation were not explicitly provided. The thermal and electric generation type appears to have no impact on the cost of capture on a gross captured basis. The report did not consider the mechanism of steam production or heat transfer in the process; it is unclear whether ranges used to calculate emissions account for thermal losses.

2.2 General Sorbent Literature Review

The general literature review, completed in 2019, considered R&D efforts investigating different sorbents, high surface area and low pressure drop sorbent supports (such as monoliths and fibers), and solid sorbent deployment in fixed, moving, or fluidized-beds. The objective of this literature review was obtaining data to inform process assumptions regarding the sorbent adsorption, desorption, and lifetime, as well the CO_2 product purity, and pressure drop of the system. After review of the data, it was determined that there is no obvious DAC material that outperforms all others and should be the focus of this assessment. Therefore, it was decided to select parameters that were representative of the data collected and consider a generic DAC sorbent for this assessment. A sensitivity analysis was performed to explore the influence of the data ranges found in literature.

Exhibit 2-6 shows literature values for DAC sorbent adsorption capacity and assumed operating conditions. The majority of the references examined consider adsorption at ambient conditions, with inlet CO_2 concentrations ranging 300–506 ppmv CO_2. The range of sorbent adsorption capacity for the references examined spans 0.05–2.83 mole CO_2/kg sorbent, across a wide range of material types. The median of the range is 1.44 mole CO_2/kg sorbent. Based on the data, a target sorbent adsorption capacity of 1.20 mole CO_2/kg sorbent was selected.

Exhibit 2-6. Literature review adsorption characteristics

Sorbent Type	Adsorption Capacity (mol CO_2/kg sorbent)	Adsorption Conditions	Reference
Supported K_2CO_3	0.64–0.86	Ambient [400 ppm CO_2]	[8]
Amine-impregnated oxide supports	0.51–2.50	T = 25°C (77°F) [360–400 ppm CO_2]	[8]
Grafted oxide supports (amine)	0.17–1.72	T = 25°C (77°F) [400–440 ppm CO_2]	[8]
Polymer supports/ polymer-supported amines	0.14–1.04	T = 15–22°C (59–72°F) [400 ppm CO_2]	[8]
Resin supported amine	0.86–2.26	T=25°C (77°F) [400–440 ppm CO_2]	[8]
Nanofibrillated cellulose supported amines	1.11–2.13	T = 23–30°C (73–86°F) [400–506 ppm CO_2]	[8]
MOFs	0.05–2.83	T = 22–25°C (72–77°F) [390–400 ppm CO_2]	[8]
Generic	0.5–1.5	Ambient [400 ppm CO_2]	[7]
Amino-polymer	0.91	T=25°C (77°F) [400 ppm CO_2]	[9]
PEI-silica	1.18–1.66	Ambient	[10]
Triamine-silica	0.91	Dry Simulated Air [300 ppm CO_2]	[10]
Polyallylamine-silica	0.64–0.86	Dry Simulated Air [400 ppm CO_2]	[10]
Hyperbranched aminosilica	0.16–1.73	Humid Simulated Air [400 ppm CO_2]	[10]
PEI-silica	2.05	Dry Simulated Air [400 ppm CO_2]	[10]
PEI-fumed silica	1.18–1.77	Ambient	[10]

Exhibit 2-7 shows literature values for DAC sorbent desorption conditions. The desorption temperature spans a wide range 67–480°C (153–896°F). The desorption pressure spans a smaller range of 0.2–1 bar (2.9–14.5 psi). Desorption cycle times are reported from a few minutes to two hours. Regeneration energy, which will be highly dependent on sorbent properties such as the presence and type of functionalized group, ranges 0.7–7.5 GJ/tonne CO_2 (300–3,250 Btu/lb CO_2). Given the wide range of potential desorption temperatures, 100°C (212°F) was selected. As will be detailed in later sections, to achieve the adsorption capacity of 1.20 mole CO_2/kg sorbent selected previously, the adsorption cycle time required is 3 hours for Case 0B and Case 0B-EB. Since data on desorption times was limited at the onset of the work, to simplify the total adsorption/desorption cycle time, a desorption time equivalent to one tenth of the full adsorption/desorption cycle time was selected: 0.3 hours. A sensitivity on capital cost, which is influenced by cycle times is performed. A regeneration energy of 4.3 GJ/tonne CO_2 (1,847 Btu/lb CO_2) was selected; this value is near the median of the regeneration energy range.

Exhibit 2-7. Literature review desorption characteristics

Sorbent Type	Desorption Temperature, °C	Desorption Pressure, bar	Cycle Times, min	Regeneration Energy, GJ/tonne CO_2	Reference
Amine-based	100	0.2	-	5.4–7.2	[11]
Amino-polymer	85–95	0.5–0.9	-	4.2–5.1	[11]
TRI-PE-MCM-41	110	-	Adsorption: 111	6.0	[12]
MOF (Cr)	135–480	1	Adsorption: 19	2.3	[13]
MOF (Mg)	135–480	1	Adsorption: 60	2.1	[13]
K_2CO_3/Y_2O_3	150–250	-	-	-	[11]
K_2CO_3	80–100	-	-	7.5	[11]
Unspecified	100	-	-	6.3	[11]
Generic	67–100	0.2–1	Adsorption: 8–50 Desorption: 7–35	3.4–4.8	[7]
Amino-polymer	80	-	Adsorption: 24–43	0.7–1.53	[9]

Exhibit 2-8 shows literature values for DAC sorbent lifetime and cost. Given the low technology readiness level status of DAC technology as a whole, data for sorbent lifetime and cost was relatively limited. For this assessment, a conservative sorbent life of 0.5 years was selected, and the influence of sorbent lifetime is evaluated in the sensitivity study. For sorbent cost, it is unclear if the literature reported values represent first-of-a-kind DAC sorbent cost estimates or take into account costs after commercialization. Black & Veatch recommended a generic value of \$4.0/ft^3 (\$0.09/lb) for the baseline sorbent cost. This value reflects a generic cost for sorbents used commercially and does not reflect the cost of a specific DAC sorbent. A sensitivity analysis evaluates the impact of higher sorbent cost.

Exhibit 2-8. Literature review lifetime and cost

Sorbent Type	Sorbent Lifetime, years	Sorbent Cost, $/kg	Reference
Generic	0.25–5	15–100	[7]
Amino-polymer	3	16	[9]

Exhibit 2-9 shows literature values for DAC system capture rate and resulting CO_2 purity. The capture rate varies 50–90 percent. A capture rate of 60 percent was chosen for this assessment. All references examined reported high CO_2 purity products. For the purposes of the assessment, where a generic sorbent is considered, it was assumed that the CO_2 product is of high purity that will meet pipeline transport specifications.

Exhibit 2-9. Literature review of CO_2 specifications

Sorbent Type	Capture Percent, %	CO_2 Purity, %	Reference
Amine-based	-	99.9	[11]
Amino-polymer	-	>98.5	[11]
TRI-PE-MCM-41	-	88[A]	[12]
Unspecified	-	>99	[11]
Generic	> 60	>98	[7]
Amine-based	-	95[A]	[14]
-	50	-	[15]
PEI-silica	90	-	[10]
Amino-polymer	56–61	-	[9]

[A]Only references that specified purity at the exit of the adsorber

Exhibit 2-10 shows reported values for DAC system vessel types considered in the literature, as well as pressure drops for those vessel types. The initial system design and costing was performed for Case 0 assuming a packed bed system, for simplicity. For Case 0, the vessel diameter required is 18.3 meters (60 feet), with a sorbent bed depth of 1.5 meters (5 feet). The vessel pressure drop is 3.5 kPa (0.51 psi). The air handling duct pressure drop is assumed to be 1.3 kPa (0.19 psi), for a total system pressure drop that the air fan must overcome of 4.8 kPa (0.7 psi). A second case (Case 0B) assuming a monolith contactor with a pressure drop more in line with literature-reported values was also evaluated. In this case, the vessel diameter required is 18.3 meters (60 feet), with a sorbent bed depth of 0.6 meters (2 feet). The vessel pressure drop is 625 Pa (0.09 psi), for a total system pressure drop that the air fan must overcome of 1.9 kPa (0.3 psi).

Exhibit 2-10. Literature review of DAC system types and pressure drop

Capture System Type	Pressure Drop, Pa (psi)	Reference
-	300–1,400 (0.04–0.2)	[7]
Radial flow reactor	348–681 (0.05–0.1)	[9]
Monolithic contactor	100 (0.01)	[12]
Circulating fluidized-bed/bubbling fluidized-bed	1,592 (0.23)	[10]
-	280 (0.04)	[15]
Monolithic contactor	-	[13]

A summary of the process parameters and system assumptions made for the DAC sorbent case study presented in this report is shown in Exhibit 2-11.

Exhibit 2-11. NETL sorbent-based DAC system assumptions

System Parameter	Value	
	Case 0 & Case 0-EB	Case 0B & Case 0B-EB
Adsorber Type	Packed Bed	Monolith
System Pressure Drop, psi (in. H_2O)[A]	0.7 (19.4)	0.3 (7.78)
System Capture Fraction[B]	0.6	
CO_2 Product Purity	Meets pipeline specification without purification	
Sorbent Adsorption Temperature	Ambient[C]	
Sorbent Adsorption Capacity, mol CO_2/kg sorbent (lb CO_2/lb sorbent)	1.2 (0.053)	
Sorbent Desorption Temperature, °C (°F)	100 (212)	
Sorbent Regeneration Energy GJ/tonne CO_2 (Btu/lb CO_2)	4.3 (1,847)	
Sorbent Lifetime, years	0.5	
Sorbent Cost, \$/ft^3 (\$/lb)	4.0 (0.09)	

[A]Includes pressure drop across ducting and DAC vessels
[B]The DAC CO_2 product purity is assumed to meet CO_2 pipeline purity requirements without additional processing
[C]Ambient air at 15°C (59°F) is pressurized through the air fan, and after pressurization, has a stream temperature of ~21°C (~70°F). No cooling is done to reduce the temperature before it enters the adsorber

3 Design Basis

3.1 Site and Fuel Characteristics

The cases considered in this study are assumed to be at a generic plant site in the midwestern United States, with site characteristics and ambient conditions as presented in Exhibit 3-1 and Exhibit 3-2. The ambient conditions are the same as International Organization for Standardization (ISO) conditions.

Exhibit 3-1. Site characteristics

Parameter	Value
Location	Greenfield, Midwestern U.S.
Topography	Level
Case 0 Size (DAC), acres	52
Case 0-EB Size (DAC), acres	42
Transportation	Rail or Highway
Water	50% Municipal and 50% Ground Water

Exhibit 3-2. Site ambient conditions

Parameter	Midwest ISO		
	BBR4 [16]	DAC	
Elevation, m (ft)	0 (0)	0 (0)	
Barometric Pressure, MPa (psia)	0.101 (14.696)	0.101 (14.696)	
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)	15 (59)	
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)	10.8 (51.5)	
Design Ambient Relative Humidity, %	60	60	
Cooling Water Temperature, °C (°F)[A]	15.6 (60)	15.6 (60)	
Air composition	**Mass %**		**Mole %**
N_2	75.055	74.983	77.243
O_2	22.998	23.050	20.784
Ar	1.280	1.272	0.919
H_2O	0.616	0.633	1.014
CO_2	0.050	0.062	0.040 (403.9 ppmv)
Total	**100.00**	**100.00**	**100.00**

[A]The cooling water temperature is the cooling tower cooling water exit temperature. This is set to 4.8°C (8.5°F) above ambient wet bulb conditions in ISO cases

NETL's Bituminous Baseline Revision 4 (BBR4) provides a starting point for the ambient conditions for the plant. [16] Adjustments to the air composition were made based on more recent atmospheric data to reflect current concentrations of CO_2 in the atmosphere. An atmospheric CO_2 content of 403.9 ppmv is assumed for the cases in this study.

The land area for the DAC plant in reference Case 0 and Case 0-EB is assumed to be 52 acres and 42 acres, respectively, based on plant layout drawings for the configurations considered.

In Case 0 and Case 0B, natural gas is utilized as the fuel for the combustion turbine, and its composition is presented in Exhibit 3-3. The natural gas properties are taken from the 2019 revision of the Quality Guidelines for Energy System Studies (QGESS): Specification for Selected Feedstocks. [17]

Exhibit 3-3. Natural gas composition

Component		Volume Percentage	
Methane	CH_4	93.1	
Ethane	C_2H_6	3.2	
Propane	C_3H_8	0.7	
n-Butane	C_4H_{10}	0.4	
Carbon Dioxide	CO_2	1.0	
Nitrogen	N_2	1.6	
Methanethiol[A]	CH_4S	$5.75x10^{-6}$	
	Total	**100.0**	
	LHV	**HHV**	
kJ/kg (Btu/lb)	47,201 (20,293)	52,295 (22,483)	
megajoule/ standard cubic meter (Btu/scf)	34.52 (927)	38.25 (1,027)	

[A]The sulfur content of natural gas is primarily composed of added Mercaptan (methanethiol [CH_4S]) with trace levels of hydrogen sulfide (H_2S) [18]
Note: Fuel composition is normalized, and heating values are calculated using Aspen

The levelized natural gas price is $4.19/GJ ($4.42/MMBtu) on an HHV basis, delivered to the Midwest. [19] Fuel costs are levelized over an assumed 30-year plant operational period with an assumed on-line year of 2023.

3.2 Environmental Targets

The environmental targets that would be enforced for a plant of the type presented in this study are presently unclear. However, NETL's BBR4 presents air emission targets for natural gas combined cycle (NGCC) plants, and these targets are reproduced for reference in Exhibit 3-4. [16]

Exhibit 3-4. NGCC emissions targets [16]

Pollutant	NGCC (lb/MWh-gross)
SO_2	0.90
NOx	0.43
PM (Filterable)	N/A
Hg	N/A
HCl	N/A

These air emission targets for NGCC power plants were applied when assessing the air emissions produced by the DAC plant.

3.3 Grid Electricity Emissions Profile

Initial system configurations considered during development of the DAC sorbent case considered purchasing electricity from the grid rather than generating electricity on site. To evaluate the net CO_2 emissions from these cases and determine whether the candidate configurations were net negative processes, average grid emissions data are needed. The NAS report provided assumed emissions profiles for multiple electricity generating sources. NETL's Grid Mix Explorer tool also provides emissions profiles for various generating sources; Exhibit 3-5 shows a comparison of the assumed emissions by generating type from these two references.

Exhibit 3-5. Assumed emissions profile by generating type

Generating Type	Assumed Emissions kg CO_2/MWh (lb CO_2/MWh)	
	NAS Report [7]	NETL Grid Mix Explorer [20]
Natural Gas	450 (992)	506 (1,116)
Coal	950 (2,094)	1,074 (2,368)
Nuclear	12 (26)	7 (15)
Solar	25 (55)	38 (84) [thermal]; 48 (106) [photovoltaic]
Wind	11 (24)	17 (37)
Hydro	-	17 (37)
Petroleum	-	1,124 (2,478)
Geothermal	-	118 (260)

The NETL Grid Mix Explorer also provides the grid electrical composition by generating type for various years, regions, and other assumptions. Outputs from the tool are shown in Exhibit 3-6.

Exhibit 3-6. NETL Grid Mix Explorer grid composition and net emissions factors

Generating Type	Grid Mix by Generating Type (%) [20]				
	2014 U.S Consumption Mix	2014 U.S. Generation Mix	2014 North America Mix	2020 U.S. Mix	2020 Midwest Reliability Council
Coal	38.9	39.4	36.2	26	44
Natural Gas	27.7	28.1	25.2	35	9
Nuclear	19.7	19.8	19.6	20	10
Petroleum	1	1.1	1	0	0
Hydro	7.4	6.3	13	7	5

Generating Type	Grid Mix by Generating Type (%) [20]				
	2014 U.S Consumption Mix	2014 U.S. Generation Mix	2014 North America Mix	2020 U.S. Mix	2020 Midwest Reliability Council
Wind	4.5	4.5	4.2	8	30
Solar Photovoltaic	0.4	0.4	0.3	2	1
Solar Thermal	0.1	0.1	0.1	0	0
Geothermal	0.4	0.4	0.3	0	0
Other Renewable	-	-	-	1	1
Total	**100.1**	**100.1**	**99.9**	**99.0**	**100**
CO_2 Emissions, kg/MWh (lb/MWh)	573 (1,264)	581 (1,282)	532 (1,174)	470 (1,037)	525 (1,158)

The data show that the grid mix CO_2 emissions can be variable by year, region, and other factors, and the range of CO_2 emissions shown spans 470–581 kg CO_2/MWh (1,037–1,282 lb CO_2/MWh).

3.4 DAC Plant Size

The most common industrial DAC plant size proposed in the literature appears to be 1 M tonnes CO_2 removed/yr (1.1 M tons/yr). However, the minimum threshold for a DAC facility to qualify for 2018 45Q tax credits is a CO_2 product flow rate of 100,000 tonnes CO_2/yr (110,230 tons/yr). [4] Given the immaturity of the technologies reported in the literature, and the unknowns regarding scale-up of these technologies to an industrial scale, the minimum 2018 45Q threshold for tax credit qualification of 100,000 tonnes CO_2/yr was selected as the target net CO_2 removal rate design point. Since this is a net removal target, the gross CO_2 removal rate from the air (and, therefore, the actual CO_2 product flow rate from the DAC plant) will be higher. The excess CO_2 required to be removed from the air in order to meet the net removal target will be dependent on many factors, including electrical auxiliary load, plant efficiency, system configuration (e.g., electricity generation on-site versus purchased power from the grid), and sorbent performance characteristics.

For perspective on the selected DAC plant size, Case B31A from NETL's BBR4 (a 727-MWnet 2017 F-Class combustion turbine-based NGCC, without CO_2 capture equipment) emits 1.7 M tonnes/yr (1.9 M tons/yr) of CO_2, or 0.35 tonnes/MWh_{net} (0.39 tons/MWh_{net}). The 100,000 tonnes CO_2/yr (110,230 tons/yr) DAC plant size selected is equivalent to 33.3 MW_{net} worth of flue gas CO_2 from Case B31A, or 4.6 percent of the net plant output.

3.5 CO_2 Transport and Storage

The cost of CO_2 transport and storage (T&S) in a deep saline formation is estimated using the Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM)/NETL CO_2 Transport Cost Model (CO_2 Transport Cost Model) and the FECM/NETL CO_2 Saline Storage Cost

Model (CO_2 Storage Cost Model). Additional detail on development of these costs is available in the 2019 revision of the QGESS: Carbon Dioxide Transport and Storage Costs in NETL Studies. [21]

Due to the variances in the geologic formations that make up saline formations across the United States, the cost to store CO_2 will vary depending on location. Storage cost results from the CO_2 Storage Cost Model align with generic plant locations from the NETL studies:

- Midwest plant location – Illinois Basin
- Texas plant location – East Texas Basin
- North Dakota plant location – Williston Basin
- Montana plant location – Powder River Basin

The far-right column of Exhibit 3-7 shows the total T&S costs used in NETL system studies for each plant location rounded to the nearest whole dollar. Only the $10/tonne value is used in this report since all cases are assumed to be located in the Midwest.

Exhibit 3-7. CO_2 transport and storage costs

Plant Location	Basin	Transport (2018 $/tonne)	Storage Cost at 25 Gt (2018 $/tonne)	T&S Value for System Studies[A] (2018 $/tonne)
Midwest	Illinois	2.07	8.32	10
Texas	East Texas		8.66	11
North Dakota	Williston		12.98	15
Montana	Powder River		19.84	22

[A]The sum of transport and storage costs rounded to the nearest whole dollar

3.6 Cost of CO_2 Capture Calculation Methodology

NETL has provided guidance on methods for calculating cost of electricity (COE) for power plants in NETL techno-economic analyses in its QGESS: Cost Estimation Methodology for NETL Assessment of Power Plant Performance. [22] The COE equation used is provided below.

$$COE = CC + OM + FP \qquad \textbf{(1)}$$

Where:

CC = capital charges for the plant

OM = operation and maintenance costs for the plant

FP = fuel costs for the plant

The annual operation and maintenance and fuel costs for the plant are calculated based on system performance and added to the capital charges.

The capital charge portion of COE is calculated by multiplying a fixed charge rate (FCR) by the plant total as-spent cost (TASC). TASC is calculated by taking the plant total overnight cost (TOC) and multiplying by a TASC/TOC ratio. The determination of the FCR and TASC/TOC ratio is presented in the referenced QGESS and is based on financial parameter assumptions common to the power industry. The product of FCR and TASC/TOC is referred to as the fixed charge factor.

For the purposes of calculating a cost of CO_2 capture (COC) that the DAC plant can expect to achieve, the COE methodology outlined in the QGESS is applied. The FCR used in these calculations is 0.0707 and the TASC/TOC ratio used is 1.093. These values were generated for a plant with a three-year construction period and are applied to NGCC cases in other NETL studies. [16] A sensitivity study on the FCR is presented to bound the potential impacts of industry-specific financial parameter assumptions on the resulting COC. The COC does not account for any credits or offsets such as those provided by 45Q, California's Low Carbon Fuel Standard or any other scheme. All costs are reported in 2019 dollars.

The equation shown below provides the full calculation for the COC for the DAC plant:

$$Cost\ of\ CO_2\ Capture\ (\frac{\$}{tonne}) = \frac{(FCR)(TASC)+OC_{FIX}+(CF)(OC_{VAR})+(CF)(FP)}{(CF)(F_{CO2})} \quad \textbf{(2)}$$

Where:

- FCR = fixed charge rate taken from the referenced QGESS [22]
- TASC = total as-spent cost
- OC_{FIX} = the sum of all first-year-of-operation fixed annual operating costs
- CF = plant capacity factor, assumed to be constant (or levelized) over the operational period; expressed as a fraction
- OC_{VAR} = the sum of all first-year-of-operation variable annual operating costs at 100 percent CF (excluding fuel), offset by any byproduct revenues
- FP = the sum of annual fuel costs at 100 percent CF; a natural gas price of $4.42/MMBtu is used, sourced from NETL's QGESS: Fuel Prices for Selected Feedstocks in NETL Studies [19]
- F_{CO2} = annual flow of CO_2 from the plant; for DAC_{net}, the flow from the plant is the net CO_2 removed from the atmosphere (100,000 tonnes/yr [110,230 tons/yr]); for DAC_{gross}, the flow from the plant is the gross CO_2 removed from the atmosphere; for $Plant_{gross}$, the flow from the plant is the gross DAC removal plus the CO_2 product flow from the NGCC plant

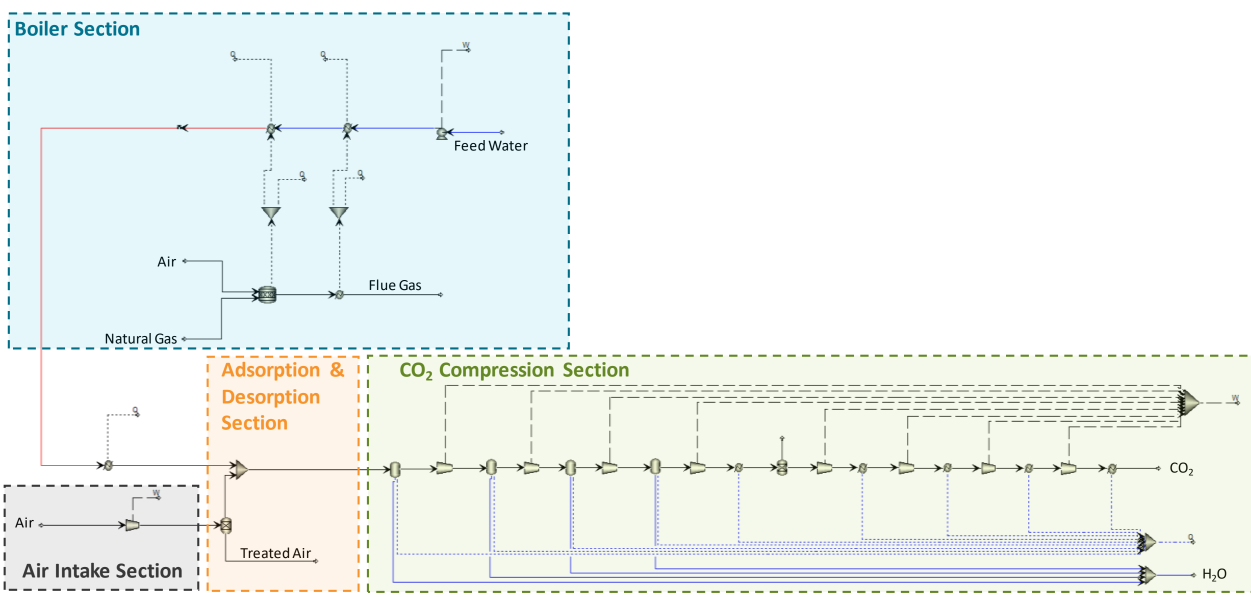
4 CASE DEVELOPMENT

Given the lack of literature data surrounding sorbent-based DAC systems, the process of determining the system configuration to be pursued for the reference case study was iterative; after generating preliminary model results, the configurations were assessed with respect to the projected net CO_2 removal potential (or net emission potential), and then process configuration adjustments were made. The most reasonable configuration if these systems were to be deployed in the near term was selected. Section 4.1 details this iterative process and provides perspective on why certain process configurations were excluded from consideration.

4.1 CANDIDATE PROCESS CONFIGURATIONS

The initial process configuration considered examined the use of a package boiler to provide steam for the DAC system, and the steam was direct use (i.e., directly contacting the sorbent). There was no CO_2 capture from the flue gas of the package boiler. Given the unknowns surrounding the performance and stability of the generic sorbent pursued, the steam for sorbent regeneration was initially assumed to not condense within the adsorber vessels. It was unclear whether the sorbent would be able to handle liquid water on its surface. Air would be provided by an inlet fan and sent to the adsorber vessels. The CO_2 product and steam would exit the adsorber during regeneration, the steam would be condensed, and the CO_2 product compressed. A process flow diagram of this configuration is shown in Exhibit 4-1.

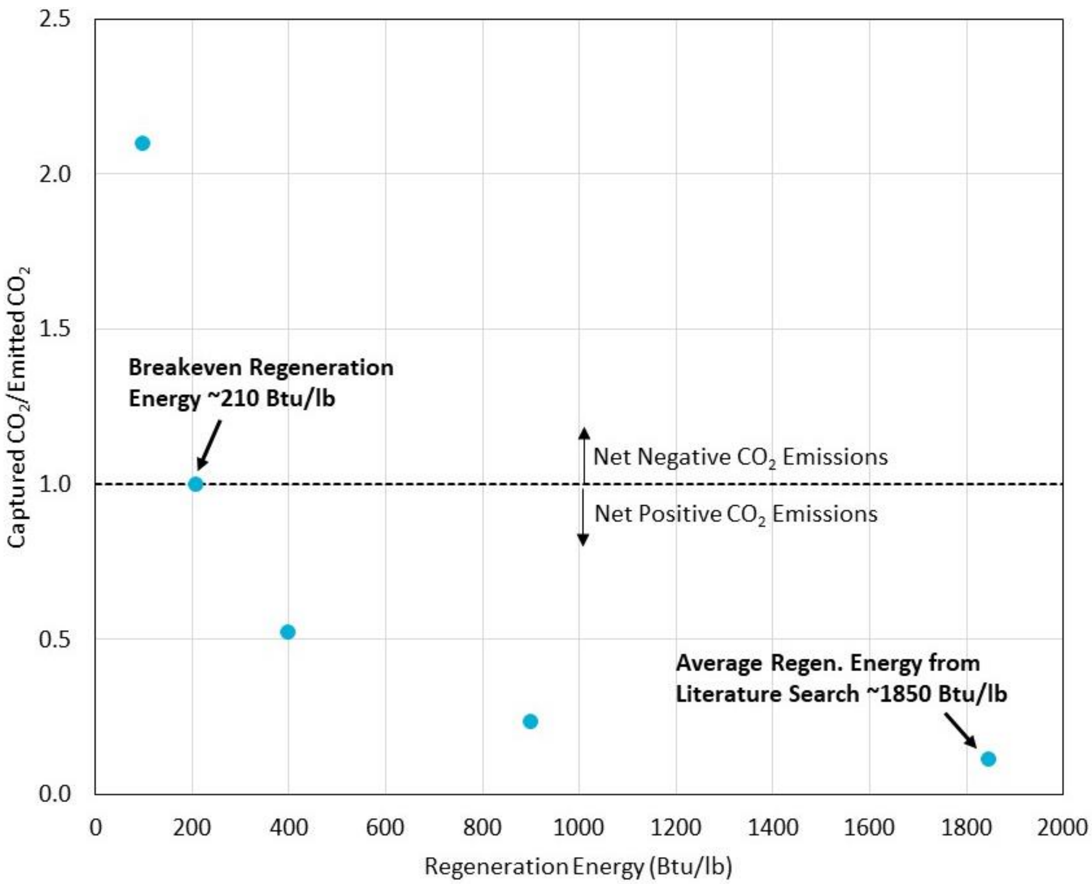
Exhibit 4-1. Initial iteration of DAC process configuration (not selected)



The sorbent regeneration energy assumed was ~4.3 GJ/tonne CO_2 (~1,850 Btu/lb CO_2). To provide the necessary heat for regeneration, while maintaining the steam exiting the adsorber in vapor form, it was determined that the system would be a net CO_2 producer given the emissions resulting from the boiler to generate the steam requirement. As shown in Exhibit 4-2, at the assumed regeneration energy, the fraction of captured CO_2 (from DAC) to emitted CO_2

(from the boiler) was ~0.1. A value below 1 indicates that the system is a net CO_2 producer. At a regeneration energy of ~0.5 GJ/tonne CO_2 (~210 Btu/lb CO_2), a ratio of 1 was achieved. This indicates that a significant reduction in regeneration energy would be required to allow the system to be a net remover of CO_2.

Exhibit 4-2. Sensitivity of initial configuration to varying regeneration energy



Given this result, the process configuration shifted from direct use of steam for regeneration to indirect use of steam. Steam heating coils were included within the adsorber to allow the steam to condense and utilize the latent heat of vaporization for sorbent regeneration.

The next section of the candidate configuration to be assessed was the electrical auxiliary load. For a 1 M tonnes CO_2/yr (1.1 M tons/yr) capacity monolith sorbent contactor system, assuming a 60 percent capture rate in the adsorbers, requires that approximately 408 M kg/hr (906 M lb/hr) of inlet air be pressurized from ambient 101.4 kPa (14.7 psia) to 103.3 kPa (14.8 psia) to overcome the assumed 1.9 kPa (0.09 psi) system pressure drop. This requires an auxiliary load of approximately 327 MW, plus an auxiliary load of 17 MW to compress the target CO_2 flow to pipeline specifications 15.3 MPa (2,200 psig), totaling 344 MW of electrical auxiliary load before accounting for balance of plant auxiliary loads relating to the cooling system. Assuming this electrical auxiliary load would be satisfied exclusively via purchased electricity from the grid, using the lowest grid mix CO_2 emission profile of 470 kg CO_2/MWh (1,037 lb CO_2/MWh) (2020 U.S. Mix), shown previously in Section 3.3, results in approximately 1.42 M tonnes of CO_2/yr

(1.56 M tons/yr) being emitted from the power generating point sources. Thus, the candidate configuration would be a net 0.42 M tonnes CO_2/yr (0.46 M tons/yr) emitter to the atmosphere. For perspective, the monolith contactor case would require an average grid emission profile of approximately 332 kg CO_2/MWh (732 lb CO_2/MWh) to achieve a point source emission of 1 M tonnes CO_2/yr (1.1 M tons/yr) emitted from the power generating point sources, and for a true net-negative technology, would require a profile below this emission rate.

This result suggests that for DAC processes to be configured to purchase electricity from the grid to satisfy all of the plant auxiliary load, the system would need to be heavily supplied by low carbon sources. While conceptually feasible, it was decided that this scenario was not a feasible scenario to represent today's potential DAC plant configurations when the capacity factors (CFs) likely required for the DAC plant to approach economic feasibility are considered. This discussion is expanded in Section 6, where sensitivity Case 0B-EB is presented; Case 0B-EB presents a scenario where the DAC steam requirement and electrical auxiliary load are fulfilled by purchased electricity.

Given these results, a more reasonable configuration if DAC systems are to be deployed in the near term comprises a dedicated NGCC plant supplying both electrical auxiliary load and steam demand, with 90 percent of flue gas CO_2 from the NGCC captured. This approach minimizes the CO_2 emissions associated with power generation and is the process configuration considered in the development of Case 0B.

5 Case 0B – Monolith Structure

5.1 Case 0B – Plant Configuration

Case 0B uses an NGCC plant to provide the electrical auxiliary load and steam requirements of the DAC system. Shell's Cansolv system is employed to capture 90 percent of the CO_2 from the NGCC flue gas and provide low carbon power and steam to support the demands of the DAC plant. Case 0B captures a net 100,000 tonnes CO_2/yr (110,230 tons/yr) from the atmosphere. The plant is electricity neutral; it does not produce excess electricity to sell on the grid, nor does it require purchased power to satisfy plant auxiliary loads.

Inlet air is passed through fans that provide the motive force to deliver the air to the DAC adsorber vessels, and overcome the pressure drop of the duct distribution system as well as the pressure drop of the sorbent bed. During the adsorption phase, the air exits the top of the vessels. During desorption, steam is provided to the vessels via internal heating coils and provides the driving force to desorb CO_2 from the sorbent.

The NGCC plant is modeled after the reference Case B31B presented in NETL's BBR4. [16] Sub-system descriptions for the NGCC plant can be found in the reference report and are not replicated here. There were two notable changes made from the reference Case B31B. Given the size, and electrical demand of the DAC system, only a single combustion turbine (CT) is considered. In addition, in the referenced study, a single CT provides a gross electrical output of 239 MW, which is well beyond what is required for the DAC system. The CT in the reference study was scaled down (i.e., treated as a "rubber turbine") to match the electrical requirements of the DAC system. In practice, smaller-scale CTs, such as aeroderivative CTs, would be a more technically feasible option for this type of plant. The second notable change is that the reference Case B31B considered a triple-pressure heat recovery steam generator (HRSG), supplying a triple pressure steam turbine (ST) bottoming cycle. Given the steam requirements of the DAC system, the HRSG was adjusted to produce saturated steam at a single pressure (0.51 MPa [73.5 psia]). Any steam requirements of the system that exceeded the temperature of this steam (e.g., Cansolv requirements for solvent purification, or triethylene glycol [TEG] dryer requirements for CO_2 compression) were assumed to be met by superheating the low-pressure steam to the required temperature. Any excess steam generated by the HRSG that was not needed by Shell's Cansolv unit or the DAC process was sent to a single-stage low-pressure steam cycle. The combined electrical output of the ST and CT was adjusted such that it met the total plant auxiliary loads exactly, with no excess available for sale to the grid, or deficit requiring purchase from the grid.

The DAC plant layout was designed to optimize efficiency and the overall footprint of the facility. This is accomplished by co-locating components to the greatest extent practical. Examples include placing the NGCC components (e.g., CT building, ST building, and cooling towers) in as close proximity as would be practical. This arrangement minimizes the amount of piping material needed for the various steam, feedwater, and cooling water systems. The array of adsorber vessels is set up in a square pattern to minimize plant area while also providing suitable space for access and maintenance in and around the vessels. An estimated wall-to-wall separation of 3 m (10 feet) is reflected in the plant layout. The facility layout was further optimized through the location of the various sub-process buildings. Mirroring other chemical process facilities, the administration building (including the control room) is co-located near the NGCC equipment. The warehouse, machine shop, and ancillary storage building is located on the west side of the vessel array to safely demarcate maintenance activities (i.e., welding, volatile material storage, maintenance vehicle storage, etc.) separate from the critical facility equipment (CT, ST, gas compressors, etc.). More detailed discussion on the layout and a site layout drawing for Case 0, upon which Case 0B is based, are presented in Appendix A: Reference Case 0.

The following sub-sections provide additional description of sub-systems specific to the DAC portion of the process.

5.1.1 Inlet Air Handling System

The inlet air handling sub-system controls the movement of air via the use of centrifugal fans, ducting, and guillotine dampers. The system comprises 10 centrifugal fans (with one additional spare fan for a total of 11) that serve the 20 adsorber vessels in Case 0B. The ambient air enters through inlet boxes of the centrifugal fans, exits the fan to be discharged through the air duct system and from the air duct system is routed to the bottom of the adsorber vessel(s) where it is then routed vertically upward to flow across the solid-sorbent bed. Once past the bed, the ambient air exits the vessel through a short, weather-protected, circular 90-degree transition piece that safely exhausts the air back to ambient at a horizontal orientation. The fans will be operated at constant speed and flow independent of vessel operations; during the relatively short desorption process, the output of the air fans can be reduced using the inlet throttling mechanism (e.g., variable inlet vanes). The air duct will be constructed of standard carbon steel with interior and exterior stiffeners for additional support. Throughout the handling process, pressure losses will be mitigated by incorporating flow straightening devices within the duct to maintain efficiency.

5.1.2 Vessel Operations

The reactor vessel is an 18.3-meter (60-foot) diameter cylindrical container constructed from welded carbon steel plates. The vessels will be approximately 9.1 m (30 feet) tall and elevated to allow enough room for air duct and pipe routing underneath the vessel. Each vessel will also be equipped with both internal and external stiffeners. Inside the bottom of each vessel will be the fixed bed of sorbent that will be interfaced with an indirect heating element, which is heated by the steam supplied from the HRSG. Large guillotine dampers will be fitted on both inlets and outlets of each vessel to allow the vessel to provide high integrity isolation during the capture process. The vessel array characterized in Case 0B consists of 20 vessels; it has been assumed that no redundant (i.e., normally out of service) vessels have been included in the vessel array.

Sorbent is loaded into the vessel, around the heating element. The process of adsorption starts by circulating air into the open vessel from ambient. The sorbent will begin to bond and remove the CO_2 from the air as it passes through the vessel; air that passes through the bed will be exhausted out the top of the vessel. Once adsorption is complete, both dampers (inlet/outlet) will close, isolating the vessel. The adsorption process lasts for approximately 3 hours.

Desorption immediately begins, and the steam will be routed through the heating coils thereby providing the necessary regeneration energy to the sorbent. The heat will cause the sorbent to release the captured CO_2. During the heating, the CO_2 compressor will draw suction from the applicable vessels into the DAC process product gas handling system. Once desorption is complete, the sorbent is ready for the adsorption process to begin again, starting with the opening of inlet/outlet guillotine dampers and resuming the flow of ambient air. The desorption process lasts for approximately 18 minutes.

5.1.3 DAC Process Off-Gas Handling System

The safe control and handling of DAC adsorber vessel off-gas (i.e., CO_2) is managed by the DAC process off-gas handling system. This system comprises the off-gas isolation valves (one per vessel), the carbon steel piping connecting the vessels to the DAC processing areas, the DAC reciprocating compressor (one for the entire facility), a glycol-based closed-loop heat exchanger, and the compressor intercoolers. CO_2, along with other off-gas constituents will be produced from the sorbent as the regeneration energy is supplied during the desorption process. The off-gas will be routed via carbon steel piping to the DAC processing area. The gas will be cooled to remove moisture and then compressed to pipeline specifications for transmission. Assuming a dedicated DAC off-gas handling and compression system, as opposed to comingling DAC off-gas with Cansolv off-gas, allows evaluation of a standalone DAC system.

5.1.4 Sorbent Material Handling System

The material handling sub-system controls the movement and storage of the new and spent solid sorbent throughout the DAC facility. The sorbent material handling system was developed with a packed bed system in mind and the specifics are not directly applicable for a monolith-based DAC system. The cost of this subsystem was, however, included in the cost estimation for Case 0B and Case 0B-EB; it is assumed that similar costs would be incurred by a monolith handling system. Details of the sorbent material handling system can be found in Appendix A: Reference Case 0.

5.1.5 Perspective on System Assumptions

The lack of available data for DAC systems necessitated several system assumptions. Exhibit 5-1 lists several systems assumptions, their viability, potential future configuration adjustments, and how those adjustments may impact the results.

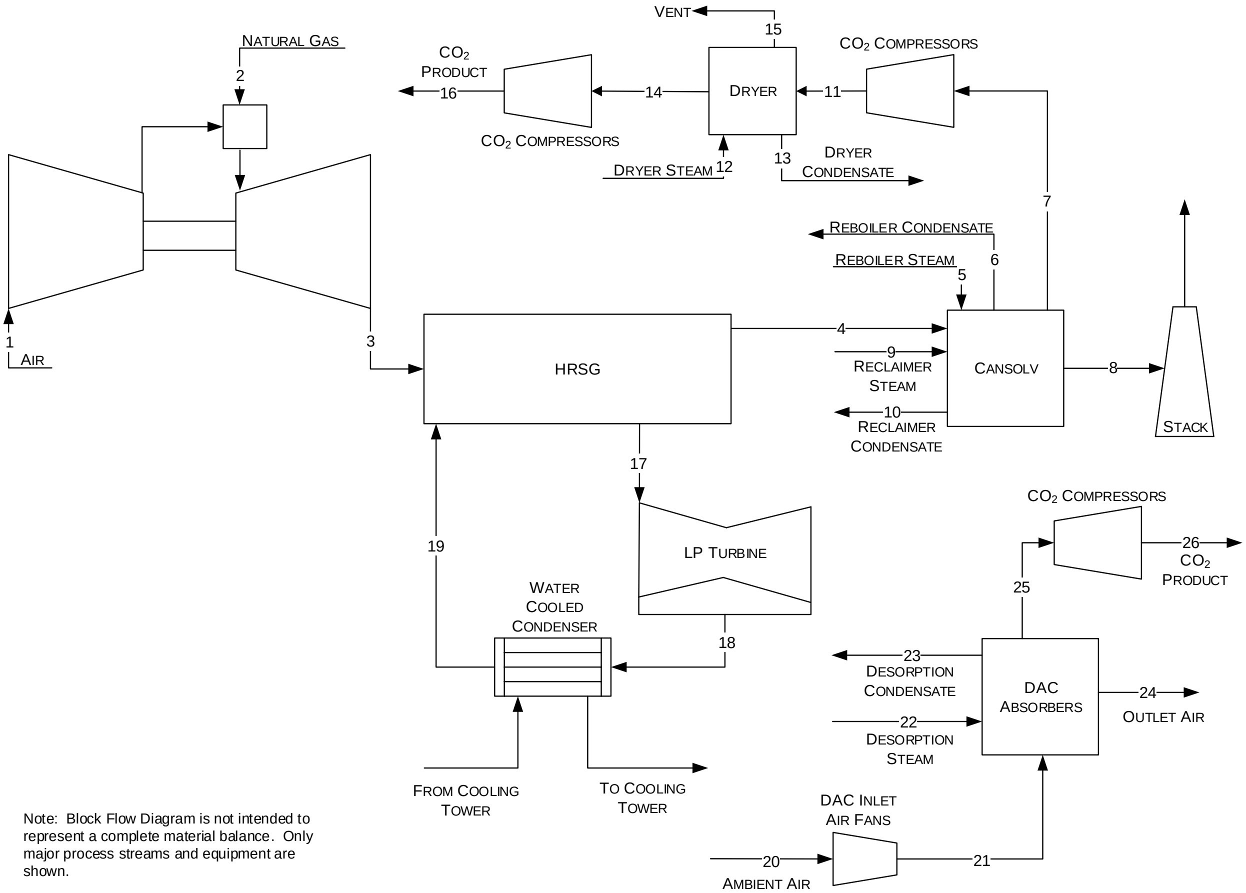
Exhibit 5-1. Perspective on DAC system assumptions

Assumption/System Component	Issues/Considerations	Potential Future Adjustments	Impact of Future Adjustments
Adsorber vessel outlet air exits the system directly from the vessel; no stack is considered, and no considerations for configuration (to limit low CO_2 content air from entering downstream air fans/vessels) were considered	Low CO_2 content air entering downstream fans/adsorbers will have a negative impact on system performance	Reconfigure layout to allow for air dispersion impacts	Layout configurations could impact cost; in this instance, there is the potential that alternate layouts could minimize duct pressure drop for the air handling system
The reference DAC plant is assumed to be compliant with ELG regulation without any additional treatment/sub-system	It is unclear how ELG would or wouldn't apply to this system; the NGCC plant is assumed compliant in the reference study, but DAC will produce water streams	Add sub-systems to treat DAC steam cycle water/DAC CO_2 compression water	Adding sub-systems will increase plant cost and COC; There are no efficiency benefits to adding compliance systems for ELG regulation
Rubber turbine from B31B reference case	In practice, off-the-shelf CT technology would need to be considered	Adjust from a scaled F-class CT to an aeroderivative	Different performance will impact overall system performance and cost; it is currently unclear whether this change would benefit the plant performance/cost
A single reciprocating compressor is used for DAC CO_2	The plant layout may require that multiple DAC CO_2 compressors be considered	Adjust layout; add DAC CO_2 compressors as needed	Adding CO_2 compressors will reduce the economy of scale benefit; capital cost and COC will increase
A dedicated scaled NGCC plant with 90 percent CO_2 capture was selected to provide steam and power to the system	Other reasonable configurations could be considered, such as implementation of a full-scale NGCC plant with power sales, and utilizing higher CO_2 capture rates from flue gas	Consider implementation of full-scale NGCC and higher CO_2 capture rates from flue gas	These changes could potentially increase process efficiency and reduce COC

5.2 Case 0B – Process Description and Performance Results

In this section, the Case 0B system is described. The system description follows the block flow diagram (BFD) in Exhibit 5-2 and stream numbers reference the same exhibit. Exhibit 5-3 provides process data for the numbered streams in the BFD. The DAC portion of the process considers 20 adsorber vessels and 10 air fans, but the flow rates in the stream table represent the total system. Case 0B captures a net 100,000 tonnes CO_2/yr from the atmosphere, has a gross capture rate of 113,900 tonnes CO_2/yr with 125,090 tonnes CO_2/yr captured by the Cansolv system.

Exhibit 5-2. Case 0B BFD, sorbent-based monolith DAC system



Ambient air (stream 1) is supplied to an inlet filter and compressed before being combined with natural gas (stream 2) in the dry low-NOx burners (LNBs), which is operated to control the rotor inlet temperature at 1,423°C (2,594°F). The flue gas exits the turbine at 624°C (1,156°F) (stream 3) and passes into the HRSG. The single-pressure HRSG generates 0.51 MPa (73.5 psia) steam, the majority of which is directly used in the Cansolv unit (stream 5) for solvent regeneration, and in the DAC adsorbers (stream 22) for sorbent regeneration. A small portion of the steam is superheated for use in the Cansolv solvent reclaimer (stream 9) and CO_2 TEG dryer (stream 12). The balance of the steam generated by the HRSG is sent to a small steam bottoming cycle (stream 17). Flue gas exits the HRSG at 167°C (332°F) (stream 4) and passes to Shell's Cansolv system, where 90 percent of the flue gas CO_2 is removed (stream 7), dried, and compressed to 15.2 MPa (2,200 psig) (stream 16). The purified flue gas leaves through the stack (stream 8). Ambient air (stream 20) is sent through fans and a duct system to distribute air to the 20 DAC adsorber vessels (stream 21). During steady-state operations, vessels operating in adsorption mode (3-hour cycle) receive air from the fans. Vessels not in adsorption mode will be in desorption mode (18-minute cycle) and utilize steam from the HRSG (stream 22) to drive CO_2 from the sorbent. The product CO_2 is pulled from the adsorber vessels to the CO_2 compressor (stream 25), where it is compressed to 15.2 MPa (2,200 psig) (stream 26). Assuming a dedicated DAC CO_2 compression system allows evaluation of a standalone DAC system.

Exhibit 5-3. Case 0B stream table, sorbent-based monolith DAC system

	1	2	3	4	5	6	7	8	9	10	11	12	13
V-L Mole Fraction													
Ar	0.0092	0.0000	0.0088	0.0088	0.0000	0.0000	0.0000	0.0097	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.9310	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0004	0.0100	0.0409	0.0409	0.0000	0.0000	0.9865	0.0045	0.0000	0.0000	0.9961	0.0000	0.0000
H_2O	0.0101	0.0000	0.0877	0.0877	1.0000	1.0000	0.0135	0.0358	1.0000	1.0000	0.0039	1.0000	1.0000
N_2	0.7724	0.0160	0.7421	0.7421	0.0000	0.0000	0.0000	0.8174	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.2079	0.0000	0.1204	0.1204	0.0000	0.0000	0.0000	0.1326	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	9,954	403	10,369	10,369	1,205	1,205	387	9,414	9	9	383	1	1
V-L Flowrate (kg/hr)	287,236	6,988	294,223	294,223	21,713	21,713	16,897	267,095	166	166	16,830	10	10
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	27	625	167	153	152	30	30	216	152	29	204	152
Pressure (MPa, abs)	0.10	2.96	0.11	0.10	0.51	0.49	0.20	0.10	0.50	0.49	3.04	0.50	0.49
Steam Table Enthalpy (kJ/kg)[A]	30.65	22.04	833.27	315.61	2,773.62	635.56	38.37	87.89	2,897.38	635.56	-4.49	2,875.21	635.56
Aspen Plus Enthalpy (kJ/kg)[B]	-100.89	-4,487.18	-647.50	-1,165.16	-13,197.72	-15,388.27	-8,964.01	-362.04	-13,073.97	-15,388.27	-8,978.11	-13,096.14	-15,388.27
Density (kg/m^3)	1.2	22.1	0.4	0.8	2.7	861.1	3.5	1.1	2.3	861.1	63.6	2.3	861.1
V-L Molecular Weight	28.857	17.328	28.376	28.376	18.015	18.015	43.658	28.372	18.015	18.015	43.909	18.015	18.015
V-L Flowrate (lb-mol/hr)	21,945	889	22,859	22,859	2,657	2,657	853	20,754	20	20	845	1	1
V-L Flowrate (lb/hr)	633,246	15,405	648,651	648,651	47,868	47,868	37,251	588,843	366	366	37,103	23	23
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	80	1,156	332	308	305	86	87	420	305	85	400	305
Pressure (psia)	14.6	430.0	15.5	14.8	73.5	70.6	28.9	14.8	72.5	70.6	441.1	72.5	70.6
Steam Table Enthalpy (Btu/lb)[A]	13.2	9.5	358.2	135.7	1,192.4	273.2	16.5	37.8	1,245.6	273.2	-1.9	1,236.1	273.2
Aspen Plus Enthalpy (Btu/lb)[B]	-43.4	-1,929.1	-278.4	-500.9	-5,674.0	-6,615.8	-3,853.8	-155.6	-5,620.8	-6,615.8	-3,859.9	-5,630.3	-6,615.8
Density (lb/ft^3)	0.076	1.380	0.025	0.049	0.166	53.757	0.218	0.071	0.141	53.757	3.971	0.145	53.757

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit 5-3. Case 0B stream table, sorbent-based monolith DAC system (continued)

	14	15	16	17	18	19	20	21	22	23	24	25	26
V-L Mole Fraction													
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0092	0.0092	0.0000	0.0000	0.0092	0.0000	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.9995	0.0500	0.9995	0.0000	0.0000	0.0000	0.0004	0.0004	0.0000	0.0000	0.0002	1.0000	1.0000
H_2O	0.0005	0.9500	0.0005	1.0000	1.0000	1.0000	0.0101	0.0101	1.0000	1.0000	0.0101	0.0000	0.0000
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7724	0.7724	0.0000	0.0000	0.7726	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2079	0.2079	0.0000	0.0000	0.2079	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	382	1	382	562	562	3,442	1,425,001	1,425,001	1,665	1,665	1,424,653	348	348
V-L Flowrate (kg/hr)	16,803	26	16,803	10,125	10,125	62,015	41,120,789	41,120,789	30,000	30,000	41,105,492	15,297	15,297
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	29	29	30	153	42	42	15	18	153	152	18	100	30
Pressure (MPa, abs)	2.90	3.04	15.27	0.51	0.01	0.01	0.10	0.10	0.51	0.49	0.10	0.10	15.27
Steam Table Enthalpy (kJ/kg)[A]	-6.32	137.79	-231.09	2,773.62	2,193.86	174.91	30.65	33.52	2,773.62	635.56	33.53	86.50	-231.33
Aspen Plus Enthalpy (kJ/kg)[B]	-8,969.87	-15,225.37	-9,194.65	-13,197.72	-13,777.49	-15,896.28	-100.93	-98.06	-13,197.72	-15,388.27	-94.75	-8,875.57	-9,193.41
Density (kg/m^3)	60.1	375.2	630.1	2.7	0.1	977.6	1.2	1.2	2.7	861.1	1.2	1.5	628.8
V-L Molecular Weight	43.997	19.315	43.997	18.015	18.015	18.015	28.857	28.857	18.015	18.015	28.853	44.010	44.010
V-L Flowrate (lb-mol/hr)	842	3	842	1,239	1,239	7,589	3,141,589	3,141,589	3,671	3,671	3,140,823	766	766
V-L Flowrate (lb/hr)	37,044	58	37,044	22,323	22,323	136,720	90,655,822	90,655,822	66,140	66,140	90,622,098	33,724	33,724
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	85	85	86	308	107	107	59	64	308	305	64	212	86
Pressure (psia)	421.1	441.1	2,214.7	73.5	1.0	1.0	14.7	15.1	73.5	70.6	14.8	14.8	2,214.7
Steam Table Enthalpy (Btu/lb)[A]	-2.7	59.2	-99.4	1,192.4	943.2	75.2	13.2	14.4	1,192.4	273.2	14.4	37.2	-99.5
Aspen Plus Enthalpy (Btu/lb)[B]	-3,856.4	-6,545.7	-3,953.0	-5,674.0	-5,923.3	-6,834.2	-43.4	-42.2	-5,674.0	-6,615.8	-40.7	-3,815.8	-3,952.5
Density (lb/ft^3)	3.755	23.421	39.338	0.166	0.004	61.031	0.076	0.077	0.166	53.757	0.076	0.091	39.252

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Overall plant performance is summarized in Exhibit 5-4; Exhibit 5-5 provides a detailed breakdown of the auxiliary power requirements.

Exhibit 5-4. Case 0B plant performance summary

Performance Summary	
Combustion Turbine Power, MWe	36
Steam Turbine Power, MWe	2
Total Gross Power, MWe	**37**
NGCC CO_2 Capture/Removal Auxiliaries, kWe	800
NGCC CO_2 Compression, kWe	1,290
DAC Air Fans, kWe	32,810
DAC CO_2 Compression, kWe	1,690
Balance of Plant, kWe	783
Total Auxiliaries, MWe	**37**
Net Power, MWe	**0**
NGCC HHV Net Plant Efficiency, %	34.0%
NGCC HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	10,591 (10,039)
HHV Combustion Turbine Efficiency, %	35.2%
NGCC LHV Net Plant Efficiency, %	37.7%
NGCC LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	9,560 (9,061)
LHV Combustion Turbine Efficiency, %	39.0%
Steam Turbine Cycle Efficiency, %	5.47%
Steam Turbine Heat Rate, kJ/kWh (Btu/kWh)	65,764 (62,332)
Condenser Duty, GJ/hr (MMBtu/hr)	33 (31)
NGCC CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	101 (96)
Natural Gas Feed Flow, kg/hr (lb/hr)	6,988 (15,405)
HHV Thermal Input, kWt	101,503
LHV Thermal Input, kWt	91,617
NGCC Flue Gas CO_2 Captured, tonnes/yr	125,090
DAC CO_2 Removed from Air (Gross), tonnes/yr	113,900
NGCC Flue Gas CO_2 Emitted to Air, tonnes/yr	13,900
Net CO_2 Removed from Air, tonnes/yr	**100,000**

Exhibit 5-5. Case 0B plant power summary

Power Summary	
Combustion Turbine Power, MWe	36
Steam Turbine Power, MWe	2
Total Gross Power, MWe	**37**
Auxiliary Load Summary	
Circulating Water Pumps, kWe	400
Combustion Turbine Auxiliaries, kWe	80
Condensate Pumps, kWe	2
Cooling Tower Fans, kWe	210
CO_2 Capture/Removal Auxiliaries, kWe	800
CO_2 Compression, kWe	1,290
Feedwater Pumps, kWe	10
Ground Water Pumps, kWe	40
Miscellaneous Balance of Plant,[A] kWe	30
SCR, kWe	1
Steam Turbine Auxiliaries, kWe	0
Transformer Losses, kWe	10
DAC Air Fans, kWe	32,810
DAC CO_2 Compression, kWe	1,690
Total DAC Auxiliaries, MWe	**35**
Total non-DAC Auxiliaries, MWe	**3**
Total Auxiliaries, MWe	**37**
Net Power, MWe	**0**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

5.2.1 Monolith Sorbent Description

Monolith sorbent structures have been proposed throughout literature for DAC applications due to their relatively low pressure drops. Although several references exist [23], [24], [25] describing monolithic DAC systems, the primary references used to inform this case study are Rezaei et al. [26] and Kulkarni et al. [12] Rezaei describes mass transfer models and the pressure drops associated with multiple types of structured adsorbents including monoliths. Kulkarni proposes a monolith sorbent DAC system utilizing a cordierite monolith coated in an amine functionalized silica adsorbent. Monolith sorbent properties were selected based on the systems proposed in these references and are summarized in Exhibit 5-6. Exhibit 5-6 also includes the respective values assumed in Case 0 for comparison.

As suggested by Rezaei, Kulkarni, and others, the Hagen-Poiseuille equation was used to calculate the pressure drop across the monolithic adsorber in Case 0B.

Exhibit 5-6. Adsorber parameters, Case 0 and Case 0B

Parameter	Case 0	Case 0B
Superficial Velocity (ft/s)	1.30	8.18
Bed Depth (ft)	5	2
Cell Diameter (ft)	N/A	0.0048
Bed Pressure Drop (Pa)	3,516	625
System Pressure Drop, including ducting (Pa)	4,826	1,935
Reynold's Number	N/A	249
Vessel Diameter (ft)	60	60
Number of Vessels	120	20
Sorbent Loading (g-mol/kg sorbent)	1.20	1.20
Sorbent Density (lb/ft^3)	45	24
Adsorption Time (hr)	90	3
Desorption Time (hr)	10	0.3

5.2.2 Environmental Performance

Exhibit 5-7 presents a summary of the plant air emissions, which only include emissions from the NGCC plant and do not include emissions associated with CO_2-depleted air streams leaving the adsorber vessels.

Exhibit 5-7. Case 0B air emissions

Emission	kg/GJ (lb/MMBtu)	tonnes/yr (tons/yr)[A]	kg/MWh (lb/MWh)[B]	lb/lb $CO_{2\text{net captured}}$
SO_2	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
NOx	0.001 (0.003)	4 (4)	0.014 (0.030)	0.0000
Particulate	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
Hg	0.00E+0 (0.00E+0)	0.000 (0.000)	0.00E+0 (0.00E+0)	0.0000
CO	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
CO_2	5 (12)	13,901 (15,324)	50 (110)	0.1390

[A]Calculations based on an 85 percent CF
[B]Emissions based on gross power

As discussed previously in Section 3.2, it is presently unclear to what environmental targets the DAC plant would be subject. However, based on the air emission targets laid out for reference NGCC power plants, Case 0B would comply with air emission regulations for NGCC plants for SO_2 and NOx.

The natural gas was assumed to contain the domestic average value of total sulfur of 0.34 grains/100 scf ($4.71x10^{-4}$ lb of sulfur/MMBtu). [18] It was also assumed that the added CH_4S was the sole contributor of sulfur to the natural gas. No sulfur capture systems were required.

The CT considered was based on the CT reported in NETL's BBR4 and scaled for the necessary output. [16] The reference CTs were designed to achieve approximately 1.8 ppmvd NOx emissions (at 15 percent O_2) using a dry LNB burner in the CT generator (CTG)—the dry LNB burners reduce the emissions to about 9 ppmvd (at 15 percent O_2) [27]—and selective catalytic reduction (SCR) equipment; the SCR system is designed for 86.7 percent NOx reduction. [28]

The pipeline natural gas was assumed to contain no Hg or HCl, resulting in zero emissions.

The reference CT at full scale emits approximately 1.0 ppmv CO. It was assumed that particulate matter (PM) emissions are zero. The production of PM is a result of system inefficiencies and is not produced or emitted in any significant amount.

Ninety percent of the CO_2 in the NGCC flue gas is removed by Shell's Cansolv system. Sixty percent of the CO_2 in the DAC inlet air is removed by the sorbent in the DAC adsorber vessels.

The carbon balance for the plant is shown in Exhibit 5-8. The carbon input to the plant consists of carbon in the natural gas and carbon as CO_2 in the air fed to both the CT and the DAC adsorber vessels. Carbon leaves the plant as CO_2 through the NGCC and DAC stacks, the NGCC and DAC CO_2 product streams, and other vents.

Exhibit 5-8. Case 0B carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	5,047 (11,127)	NGCC Stack Gas	510 (1,123)
Air (CO_2)	48 (106)	NGCC CO_2 Product	4,585 (10,108)
DAC Air (CO_2)	6,958 (15,340)	NGCC CO_2 Dryer Vent	0.8 (1.8)
		NGCC CO_2 Knockout	0.0 (0.0)
		DAC CO_2 Product	4,175 (9,204)
		DAC Stack Gas	2,783 (6,136)
Total	**12,053 (26,573)**	**Total**	**12,053 (26,573)**

As shown in Exhibit 5-9, the sulfur content of the natural gas is insignificant. All sulfur in the natural gas is assumed to react with the Cansolv solvent and is removed from the solvent during solvent reclaiming as a waste stream.

Exhibit 5-9. Case 0B sulfur balance

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.1 (0.2)	Stack Gas	0.0 (0.0)
		Solvent Reclaiming	0.1 (0.2)
Total	**0.1 (0.2)**	**Total**	**0.1 (0.2)**

Exhibit 5-10 shows the overall water balance for Case 0B.

Exhibit 5-10. Case 0B water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	–	0.0 (0.1)	0.0 (-0.1)
CO_2 Capture System Makeup	0.0 (4.1)	–	0.0 (4.1)	–	0.0 (4.1)
CO_2 Capture Recovery	–	–	–	0.2 (45)	-0.2 (-45)
CO_2 Compression Recovery	–	–	–	0.0 (0.3)	0.0 (-0.3)
Cooling Tower	1.5 (402)	–	1.5 (402)	0.3 (90)	1.2 (312)
Total	1.5 (406)	–	1.5 (406)	0.5 (136)	1.0 (270)

5.2.3 Energy Balance

An overall plant energy balance is provided in tabular form in Exhibit 5-11.

The cooling tower load includes the condenser, capture process heat rejected to cooling water, the CO_2 compressor intercooler load for both compressors, and other miscellaneous cooling loads.

Exhibit 5-11. Case 0B overall energy balance (0°C [32°F] reference)

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
Natural Gas	365 (346)	0.2 (0.2)	–	366 (347)
NGCC Air	–	8.8 (8.3)	–	8.8 (8.3)
DAC Air	–	1,260 (1,194)	–	1,260 (1,194)
Raw Water Makeup	–	5.8 (5.5)	–	5.8 (5.5)
Auxiliary Power	–	–	135 (128)	135 (128)
Total	**365 (346)**	**1,275 (1,209)**	**135 (128)**	**1,775 (1,682)**
Heat Out GJ/hr (MMBtu/hr)				
NGCC Stack Gas	–	23 (22)	–	23 (22)
DAC Stack Gas	–	1,378 (1,306)	–	1,378 (1,306)
Sulfur	–	–	–	0.0 (0.0)
Motor Losses and Design Allowances	–	–	3.3 (3.1)	3.3 (3.1)
Cooling Tower Load[A]	–	199 (188)	–	199 (188)
NGCC CO_2 Product Stream	–	-3.9 (-3.7)	–	-3.9 (-3.7)
Deaerator Vent	–	0.0 (0.0)	–	0.0 (0.0)
DAC CO_2 Product Stream	–	-3.5 (-3.4)	–	-3.5 (-3.4)
Ambient Losses[B]	–	*2.0 (1.9)*	–	*2.0 (1.9)*
Power	–	–	135 (128)	135 (128)
Total	**–**	**1,595 (1,512)**	**138 (131)**	**1,733 (1,643)**
Unaccounted Energy[C]	–	***42 (40)***	–	*42 (40)*

[A]Includes condenser, capture process cooling loads, CO_2 compression intercooling loads, and miscellaneous cooling loads
[B]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the combustor and transformers
[C]By difference

5.2.4 Case 0B – Equipment List

Major equipment items for the total plant (NGCC plant with CO_2 capture and DAC system) are shown in the following tables. The accounts used in the equipment list correspond to the account numbers used in the cost estimates in Section 5.3. In general, the design conditions include a 10 percent contingency for flows and heat duties and a 21 percent contingency for heads on pumps and fans.

Case 0B – Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Condensate Pumps	Vertical canned	1,140 lpm @ 10 m H_2O (300 gpm @ 40 ft H_2O)	1	1
2	Boiler Feedwater Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed for IP and LP feedwater	LP water: 1,140 lpm @ 60 m H_2O (300 gpm @ 190 ft H_2O)	2	2
3	Auxiliary Boiler	Shop fabricated, water tube	18,000 kg/hr, 2.8 MPa, 343°C (40,000 lb/hr, 400 psig, 650°F)	1	0
4	Service Air Compressors	Flooded screw	13 m^3/min @ 0.7 MPa (450 scfm @ 100 psig)	2	1
5	Instrument Air Dryers	Duplex, regenerative	13 m^3/min (450 scfm)	2	1
6	Closed Cycle Cooling Heat Exchangers	Plate and frame	13 MMkJ/hr (13 MMBtu/hr)	2	0
7	Closed Cycle Cooling Water Pumps	Horizontal centrifugal	5,200 lpm @ 20 m H_2O (1,400 gpm @ 70 ft H_2O)	2	1
8	Engine-Driven Fire Pump	Vertical turbine, diesel engine	3,785 lpm @ 110 m H_2O (1,000 gpm @ 350 ft H_2O)	1	1
9	Fire Service Booster Pump	Two-stage horizontal centrifugal	2,650 lpm @ 80 m H_2O (700 gpm @ 250 ft H_2O)	1	1
10	Raw Water Pumps	Stainless steel, single suction	900 lpm @ 20 m H_2O (200 gpm @ 60 ft H_2O)	2	1
11	Filtered Water Pumps	Stainless steel, single suction	150 lpm @ 50 m H_2O (40 gpm @ 160 ft H_2O)	2	1
12	Filtered Water Tank	Vertical, cylindrical	145,000 liter (38,000 gal)	1	0
13	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	350 lpm (90 gpm)	1	0
14	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0
15	Gas Pipeline	Underground, coated carbon steel, wrapped cathodic protection	6 m^3/min @ 3.0 MPa (205 acfm @ 430 psia) 39 cm (16 in) standard wall pipe	16 km (10 mile)	0
16	Gas Metering Station	–	6 m^3/min (205 acfm)	1	0

Case 0B – Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Shell's Cansolv System	Amine-based CO_2 capture technology	324,000 kg/hr (714,000 lb/hr) 6.3 wt% CO_2 concentration	1	0
2	Shell's Cansolv LP Condensate Pump	Centrifugal	416 lpm @ 5 m H_2O (110 gpm @ 17 ft H_2O)	1	1
3	Shell's Cansolv HP Condensate Pump	Centrifugal	3 lpm @ 5 m H_2O (1 gpm @ 17 ft H_2O)	1	1
4	CO_2 Dryer	Triethylene glycol	Inlet: 4 m^3/min @ 3.0 MPa (156 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 26 kg/hr (58 lb/hr)	1	0
5	CO_2 Compressor	Integrally geared, multi-stage centrifugal	0.5 m^3/min @ 15.3 MPa, 80°C (17 acfm @ 2,217 psia, 176°F)	1	0
6	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15.3 MPa, 30°C (2,215 psia, 86°F) Duty: 3 MMkJ/hr (2 MMBtu/hr)	1	0

Case 0B – Account 6: Combustion Turbine and Accessories

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Combustion Turbine	Advanced F class w/ dry low-NOx burner	40 MW	1	0
2	Combustion Turbine Generator	Hydrogen Cooled	40 MVA @ 0.9 p.f., 18 kV, 60 Hz, 3-phase	1	0

Case 0B – Account 7: HRSG, Ductwork, and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	46 m (150 ft) high x 1.9 m (6.3 ft) diameter	1	0
2	Heat Recovery Steam Generator	Drum, single-pressure with economizer section	Main steam - 68,217 kg/hr, 0.4 MPa/153°C (150,392 lb/hr, 59 psig/308°F)	1	0
3	SCR Reactor	–	290,000 kg/hr (650,000 lb/hr)	1	0
4	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
5	Dilution Air Blowers	Centrifugal	1 m^3/min @ 108 cm WG (30 scfm @ 42 in WG)	1	1
6	Ammonia Feed Pump	Centrifugal	0.2 lpm @ 90 m H_2O (0.1 gpm @ 300 ft H_2O)	1	1
7	Ammonia Storage Tank	Horizontal tank	3,000 liter (1,000 gal)	1	0

Case 0B – Account 8: Steam Turbine and Accessories

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	2 MW 0.4 MPa/153°C/153°C (59 psig/ 308°F/308°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	2 MVA @ 0.9 p.f., 18 kV, 60 Hz, 3-phase	1	0
3	Surface Condenser	Two pass, divided waterbox including vacuum pumps and integrated deaerator	40 GJ/hr (30 MMBtu/hr), Inlet water temperature 16°C (60°F), Water temperature rise 11°C (20°F)	1	0
4	Steam Bypass	One per HRSG	50% steam flow @ design steam conditions	1	0

Case 0B – Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	39,000 lpm @ 30 m (10,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (51.5°F) wet bulb/16°C (60°F) CWT/ 27°C (80°F) HWT/ 220 GJ/hr (210 MMBtu/hr) heat duty	1	0

Case 0B – Account 11: Accessory Electric Plant

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Medium Voltage Transformer	Oil-filled	18 kV/4.16 kV, 1.3 MVA, 3-ph, 60 Hz	1	1
2	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 0.5 MVA, 3-ph, 60 Hz	1	1
3	CTG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	18 kV, 3-ph, 60 Hz	1	0

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
4	STG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	18 kV, 3-ph, 60 Hz	1	0
5	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
6	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
7	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Case 0B – Account 12: Instrumentation and Control

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser, color); Engineering printer (laser, black and white)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

Case 0B – Account 15: Direct Air Capture

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Absorbers	Sorbent, packed bed	377,000 kg/hr (831,000 lb/hr) 0.06 wt% CO_2 concentration	120	0
2	Air Fans	-	753,871 kg/hr @ 0.1 MPa, (1,662,000 lb/hr @ 15 psia)	60	1
3	CO_2 Compressor	Reciprocating compressor	0.5 m³/min @ 15.3 MPa, 118°C (16 acfm @ 2,215 psia, 244°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15.3 MPa, 30°C (2,215 psia, 86°F) Duty: 4 MMkJ/hr (3 MMBtu/hr)	1	0

5.3 Case 0B – Cost Estimate Results

Exhibit 5-12 shows a detailed breakdown of the capital costs; Exhibit 5-13 shows the owner's costs, TOC, and TASC; Exhibit 5-14 shows the initial and annual operation and maintenance (O&M) costs; Exhibit 5-15 shows the scaling parameters for DAC specific accounts, and Exhibit 5-16 shows the COC breakdown. The uncertainty of the capital cost estimates is +/-50 percent, consistent with Association for the Advancement of Cost Engineering (AACE) Class 5 cost estimates (i.e., concept screening), based on the level of engineering design performed. In all cases, this report relies on vendor cost estimates for component technologies and process equipment, corresponding to the assumption- and/or model-derived equipment specifications. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs, which can be a challenge for emerging technologies. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required. All costs are reported in 2019 dollars.

Sorbent-based direct air capture (DAC) systems are an immature technology, lacking a history of commercial deployment at scale. The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher the presented estimates. Absent demonstrated first-of-a-kind (FOAK) plant costs associated with a specific plant configuration/technology, it is difficult to explicitly project fully mature, N^{th}-of-a-kind (NOAK) values. Consequently, the cost estimates provided herein represent neither FOAK nor NOAK costs. Nevertheless, the application of a consistent methodology - and the presentation of detailed equipment specifications and costs based on contemporary sources - facilitate comparison between cases as well as sensitivity analyses to guide R&D, and generally improve upon many publicly available estimates characterized by more opaque methods and sources, and less detail.

Anticipated actual costs for projects based upon any of the cases presented herein 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 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.

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 here.

Exhibit 5-12. Case 0B total plant cost details

Case:		DAC-0B					Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
1	Sorbent Handling										
1.5	Sorbent Receive & Unload	$17	$0	$5	$0	$22	$4	$0	$4	$30	$0
1.6	Sorbent Stackout & Reclaim	$131	$0	$24	$0	$154	$31	$0	$28	$213	$2
1.7	Sorbent Conveyors	$190	$41	$46	$0	$278	$56	$0	$50	$383	$4
1.8	Other Sorbent Handling	$10	$2	$5	$0	$17	$3	$0	$3	$23	$0
1.9	Coal & Sorbent Handling Foundations	$0	$132	$174	$0	$306	$61	$0	$55	$422	$4
	Subtotal	$347	$175	$253	$0	$776	$155	$0	$140	$1,071	$11
2	Sorbent Preparation and Feed										
2.5	Sorbent Preparation Equipment	$84	$4	$17	$0	$105	$21	$0	$19	$146	$1
2.6	Sorbent Storage & Feed	$142	$0	$53	$0	$195	$39	$0	$35	$269	$3
2.9	Coal & Sorbent Feed Foundation	$0	$58	$51	$0	$109	$22	$0	$20	$151	$2
	Subtotal	$226	$62	$122	$0	$410	$82	$0	$74	$566	$6
3	Feedwater and Miscellaneous BOP Systems										
3.1	Feedwater System	$390	$668	$334	$0	$1,392	$278	$0	$250	$1,920	$19
3.2	Water Makeup & Pretreating	$834	$83	$472	$0	$1,390	$278	$0	$333	$2,001	$20
3.3	Other Feedwater Subsystems	$190	$62	$59	$0	$312	$62	$0	$56	$431	$4
3.4	Service Water Systems	$239	$457	$1,479	$0	$2,175	$435	$0	$522	$3,132	$31
3.5	Other Boiler Plant Systems	$39	$14	$36	$0	$90	$18	$0	$16	$124	$1
3.6	Natural Gas Pipeline and Start-Up System	$3,309	$142	$107	$0	$3,558	$712	$0	$640	$4,909	$49
3.7	Waste Water Treatment Equipment	$1,592	$0	$976	$0	$2,569	$514	$0	$616	$3,699	$37
3.9	Miscellaneous Plant Equipment	$4,955	$650	$2,518	$0	$8,123	$1,625	$0	$1,949	$11,697	$117
	Subtotal	$11,548	$2,077	$5,981	$0	$19,607	$3,921	$0	$4,385	$27,913	$279
5	Flue Gas Cleanup										
5.1	Shell's Cansolv Carbon Dioxide (CO_2) Removal System	$29,163	$15,349	$32,233	$0	$76,744	$15,349	$13,814	$21,181	$127,089	$1,271
5.4	Carbon Dioxide (CO_2) Compression & Drying	$7,843	$1,177	$3,254	$0	$12,273	$2,455	$0	$2,946	$17,674	$177
5.5	Carbon Dioxide (CO_2) Compressor Aftercooler	$42	$7	$18	$0	$67	$13	$0	$16	$96	$1
5.12	Gas Cleanup Foundations	$0	$49	$53	$0	$103	$21	$0	$25	$148	$1
	Subtotal	$37,048	$16,581	$35,558	$0	$89,187	$17,837	$13,814	$24,168	$145,006	$1,450

Case:		DAC-0B					Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
6	Combustion Turbine and Accessories										
6.1	Combustion Turbine Generator	$14,356	$0	$874	$0	$15,230	$3,046	$0	$2,741	$21,017	$210
6.3	Combustion Turbine Accessories	$522	$0	$32	$0	$554	$111	$0	$100	$764	$8
6.4	Compressed Air Piping	$0	$172	$39	$0	$211	$42	$0	$38	$292	$3
6.5	Combustion Turbine Foundations	$0	$180	$195	$0	$375	$75	$0	$90	$539	$5
	Subtotal	$14,878	$352	$1,139	$0	$16,370	$3,274	$0	$2,969	$22,613	$226
7	HRSG, Ductwork, and Stack										
7.1	Heat Recovery Steam Generator	$2,787	$0	$697	$0	$3,483	$697	$0	$627	$4,807	$48
7.2	Heat Recovery Steam Generator Accessories	$534	$0	$99	$0	$633	$127	$0	$114	$874	$9
7.3	Ductwork	$0	$139	$96	$0	$235	$47	$0	$42	$324	$3
7.4	Stack	$1,325	$0	$246	$0	$1,571	$314	$0	$283	$2,168	$22
7.5	Heat Recovery Steam Generator, Ductwork & Stack Foundations	$0	$103	$97	$0	$200	$40	$0	$48	$288	$3
7.6	Selective Catalytic Reduction System	$336	$141	$197	$0	$675	$135	$0	$121	$931	$9
	Subtotal	$4,982	$383	$1,432	$0	$6,798	$1,360	$0	$1,236	$9,393	$94
8	Steam Turbine and Accessories										
8.1	Steam Turbine Generator & Accessories	$504	$0	$74	$0	$578	$116	$0	$104	$798	$8
8.2	Steam Turbine Plant Auxiliaries	$4	$0	$8	$0	$12	$2	$0	$2	$16	$0
8.3	Condenser & Auxiliaries	$332	$0	$178	$0	$509	$102	$0	$92	$703	$7
8.4	Steam Piping	$800	$0	$324	$0	$1,125	$225	$0	$202	$1,552	$16
8.5	Turbine Generator Foundations	$0	$30	$50	$0	$80	$16	$0	$19	$115	$1
	Subtotal	$1,640	$30	$634	$0	$2,304	$461	$0	$420	$3,184	$32
9	Cooling Water System										
9.1	Cooling Towers	$1,807	$0	$547	$0	$2,354	$471	$0	$424	$3,249	$32
9.2	Circulating Water Pumps	$244	$0	$15	$0	$259	$52	$0	$47	$357	$4
9.3	Circulating Water System Auxiliaries	$2,985	$0	$394	$0	$3,379	$676	$0	$608	$4,663	$47
9.4	Circulating Water Piping	$0	$673	$609	$0	$1,282	$256	$0	$231	$1,769	$18
9.5	Make-up Water System	$133	$0	$171	$0	$303	$61	$0	$55	$419	$4
9.6	Component Cooling Water System	$99	$0	$76	$0	$175	$35	$0	$32	$242	$2
9.7	Circulating Water System Foundations	$0	$156	$258	$0	$414	$83	$0	$99	$596	$6
	Subtotal	$5,268	$829	$2,070	$0	$8,167	$1,633	$0	$1,495	$11,295	$113

Case:		DAC-0B						Estimate Type:		Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000						Cost Base:		September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	10					Spent Sorbent Handling System					
10.6	Spent Sorbent Storage Silos	$118	$0	$360	$0	$478	$96	$0	$86	$660	$7
10.7	Spent Sorbent Transport & Feed Equipment	$400	$0	$397	$0	$797	$159	$0	$144	$1,100	$11
10.9	Spent Sorbent Foundation	$0	$82	$101	$0	$183	$37	$0	$44	$263	$3
	Subtotal	$518	$82	$858	$0	$1,458	$292	$0	$273	$2,023	$20
	11					Accessory Electric Plant					
11.1	Generator Equipment	$442	$0	$333	$0	$775	$155	$0	$140	$1,070	$11
11.2	Station Service Equipment	$1,050	$0	$90	$0	$1,140	$228	$0	$205	$1,573	$16
11.3	Switchgear & Motor Control	$1,499	$0	$260	$0	$1,759	$352	$0	$317	$2,427	$24
11.4	Conduit & Cable Tray	$0	$362	$1,044	$0	$1,406	$281	$0	$253	$1,940	$19
11.5	Wire & Cable	$0	$541	$967	$0	$1,507	$301	$0	$271	$2,080	$21
11.6	Protective Equipment	$18	$0	$61	$0	$79	$16	$0	$14	$109	$1
11.7	Standby Equipment	$155	$0	$143	$0	$298	$60	$0	$54	$412	$4
11.8	Main Power Transformers	$113	$0	$2	$0	$115	$23	$0	$21	$159	$2
11.9	Electrical Foundations	$0	$12	$29	$0	$41	$8	$0	$9.84	$59	$1
	Subtotal	$3,276	$915	$2,930	$0	$7,121	$1,424	$0	$1,284	$9,830	$98
	12					Instrumentation and Control					
12.1	Natural Gas Combined Cycle Control Equipment	$167	$0	$106	$0	$273	$55	$0	$49	$377	$4
12.2	Combustion Turbine Control Equipment	$275	$0	$175	$0	$450	$90	$0	$81	$621	$6
12.3	Steam Turbine Control Equipment	$267	$0	$170	$0	$438	$88	$0	$79	$604	$6
12.4	Other Major Component Control Equipment	$413	$0	$263	$0	$675	$135	$34	$127	$971	$10
12.5	Signal Processing Equipment	$374	$0	$11	$0	$386	$77	$0	$69	$532	$5
12.6	Control Boards, Panels & Racks	$91	$0	$56	$0	$146	$29	$7	$27	$210	$2
12.7	Distributed Control System Equipment	$5,056	$0	$155	$0	$5,211	$1,042	$261	$977	$7,491	$75
12.8	Instrument Wiring & Tubing	$417	$334	$1,336	$0	$2,087	$417	$104	$391	$3,000	$30
12.9	Other Instrumentation & Controls Equipment	$289	$0	$670	$0	$959	$192	$48	$180	$1,378	$14
	Subtotal	$7,349	$334	$2,942	$0	$10,625	$2,125	$454	$1,981	$15,184	$152
	13					Improvements to Site					
13.1	Site Preparation	$0	$145	$3,074	$0	$3,219	$644	$0	$773	$4,636	$46

Case:		DAC-0B						Estimate Type:		Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000						Cost Base:		September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
13.2	Site Improvements	$0	$466	$615	$0	$1,081	$216	$0	$259	$1,557	$16
13.3	Site Facilities	$447	$0	$469	$0	$916	$183	$0	$220	$1,319	$13
	Subtotal	$447	$610	$4,159	$0	$5,216	$1,043	$0	$1,252	$7,511	$75
	14					Buildings and Structures					
14.1	Combustion Turbine Area	$0	$102	$54	$0	$156	$31	$0	$28	$216	$2
14.3	Steam Turbine Building	$0	$163	$217	$0	$381	$76	$0	$69	$525	$5
14.4	Administration Building	$0	$129	$87	$0	$217	$43	$0	$39	$299	$3
14.5	Circulation Water Pumphouse	$0	$10	$5	$0	$15	$3	$0	$3	$21	$0
14.6	Water Treatment Buildings	$0	$80	$73	$0	$153	$31	$0	$28	$212	$2
14.7	Machine Shop	$0	$188	$120	$0	$308	$62	$0	$55	$425	$4
14.8	Warehouse	$0	$155	$93	$0	$248	$50	$0	$45	$343	$3
14.9	Other Buildings & Structures	$0	$148	$108	$0	$256	$51	$0	$46	$353	$4
14.10	Waste Treating Building & Structures	$0	$261	$466	$0	$727	$145	$0	$131	$1,004	$10
	Subtotal	$0	$1,238	$1,224	$0	$2,462	$492	$0	$443	$3,398	$34
	15					Direct Air Capture System					
15.1	DAC Adsorption/Desorption Vessels	$0	$3,022	$2,472	$0	$5,494	$1,099	$549	$1,071	$8,213	$82
15.2	DAC CO_2 Compression & Drying	$2,273	$341	$943	$0	$3,558	$712	$356	$694	$5,319	$53
15.3	DAC CO_2 Compressor Aftercooler	$77	$12	$33	$0	$122	$24.44	$0	$22.00	$169	$2
15.4	DAC System Air Handling Duct and Dampers	$4,567	$18,266	$7,611	$0	$30,443	$6,089	$3,044	$5,936	$45,513	$455
15.5	DAC System Air Handling Fans	$29,228	$0	$1,538	$0	$30,767	$6,153	$3,077	$5,999	$45,996	$460
15.6	DAC Desorption Process Gas Handling System	$164	$700	$230	$0	$1,093	$219	$109	$213	$1,634	$16
15.7	DAC Steam Distribution System	$481	$2,054	$674	$0	$3,209	$642	$321	$626	$4,797	$48
15.8	DAC System Controls Equipment	$353	$0	$225	$0	$578	$116	$58	$113	$864	$9
	Subtotal	$37,144	$24,394	$13,726	$0	$75,264	$15,053	$7,514	$14,675	$112,506	$1,125
	Total	**$124,672**	**$48,063**	**$73,028**	**$0**	**$245,764**	**$49,153**	**$21,782**	**$54,793**	**$371,491**	**$3,715**

Exhibit 5-13. Case 0B owner's costs

Description	$/1,000	$/tonne
Pre-Production Costs		
6 Months All Labor	$3,957	$40
1-Month Maintenance Materials	$415	$4
1-Month Non-Fuel Consumables	$170	$2
1-Month Waste Disposal	$17	$0
25% of 1 Month's Fuel Cost at 100% CF	$279	$3
2% of TPC	$7,430	$74
Total	$12,268	$123
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$306	$3
0.5% of TPC (spare parts)	$1,857	$19
Total	$2,164	$22
Other Costs		
Initial Cost for Catalyst and Chemicals	$516	$5
Land	$156	$2
Other Owner's Costs	$55,724	$557
Financing Costs	$10,030	$100
Total Overnight Costs (TOC)	$452,349	$4,523
TASC Multiplier (IOU, 33 year)	1.093	
Total As-Spent Cost (TASC)	$494,258	$4,953

Exhibit 5-14. Case 0B initial and annual operating and maintenance costs

Case:	**DAC-0B**	**Sorbent DAC w/ 1x1 NGCC w/ CO_2 Capture**			**Cost Base:**	**September 2019**
Plant Size:	**100,000**	**tonnes of CO_2 captured (net)**			**Capacity Factor (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:		1.0
Operating Labor Burden:		30.00	**% of base**	Operator:		3.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		2.0
				Lab Techs, etc.:		2.0
				Total:		**8.0**
Fixed Operating Costs						
					Annual Cost	
					($)	**($/tonne-net)**
Annual Operating Labor:					$3,507,504	$35
Maintenance Labor:					$2,823,333	$28
Administrative & Support Labor:					$1,582,709	$16
Property Taxes and Insurance:					$7,429,823	$74
Total:					**$15,343,999**	**$153**
Variable Operating Costs						
					($)	**($/tonne-net)**
Maintenance Material:					$4,234,999	$42
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	-	292	$1.90	$0	$172,339	$2
Makeup and Waste Water Treatment Chemicals (ton):	-	0.87	550	$0	$148,609	$1
Ammonia (19 wt%, ton):	-	0.26	300	$0	$24,273	$0
SCR Catalyst (ft^3):	423	0.23	150	$63,477	$10,791	$0
CO_2 Capture System Chemicals[A]	Proprietary				$546,669	$5
Triethylene Glycol (gal):	w/ equip.	30	$6.80	$0	$62,338	$1
DAC Sorbent (ft^3):	113,097	620	$4.00	$452,389	$769,061	$8
Subtotal:				$515,866	$1,734,081	$17
Waste Disposal						
SCR Catalyst (ft^3):	0	0.23	$2.50	$0	$180	$0
Triethylene Glycol (gal):	0	30	$0.35	$0	$3,209	$0
Amine Purification Unit Waste (ton)	0	0.46	$38.00	$0	$5,397	$0
Thermal Reclaimer Unit Waste (ton)	0	0.041	$38.00	$0	$479	$0
DAC Sorbent (ft^3):	0	620	$0.86	$0	$165,348	$2
Subtotal:				$0	$174,613	$2
Variable Operating Costs Total:				$515,866	$6,143,693	$61
Fuel Cost						
Natural Gas (MMBtu):	0	8,312	$4.42	$0	$11,399,160	$114
Total:				**$0**	**$11,399,160**	**$114**

[A] *CO_2 Capture System Chemicals* includes Ion Exchange Resin, NaOH, and Shell's Cansolv Solvent

5.3.1 Cost Estimate Scaling

The cost estimate for Case 0B was developed using the cost estimate results for Case 0 as a basis (see Section A.2.6). Capital costs were scaled according to the guidance provided in NETL's QGESS: Capital Cost Scaling Methodology: Revision 4 Report. [29]

Black & Veatch developed capital cost estimates for all sub-accounts in Account 15 using their in-house cost estimating references, which include vendor-supplied data. Scaling of these costs are not covered in the previously referenced QGESS report [29]; therefore, this section provides additional perspective.

Exhibit 5-15 presents guidance on scaling of Account 15 capital costs. Depending on the scenario considered, scaling some of the sub-accounts in Account 15 may be a two-step process. For example, Case 0 requires 120 adsorber vessels, with an individual unit cost of $476,011 bare erected cost (BEC) per vessel. This cost is based on many parameters, including a vessel diameter of 18.3 meters (60 feet), a sorbent bed depth of 1.5 meters (5 feet), and others. When alternate cases are considered that add or subtract additional 60-foot diameter vessels, the individual unit cost should be multiplied by the number of units added to develop a new cost (e.g., moving from 120 vessels to 130 vessels should add $4,760,114 to the BEC, rather than scaling on diameter using a 0.60 exponent). However, if an alternate case is attempting to evaluate a scenario where adsorber design parameters are varied (e.g., the air velocity through the vessel) or system parameters are varied (e.g., assumed pressure drop), then the diameter of the vessels may change. In this instance where vessel diameter is changing, scaling using the recommended approach is warranted. However, if both diameter and the number of vessels is simultaneously changing, then scaling the unit cost first, and subsequently multiplying the unit cost by the new number of adsorber units, is recommended for consistency. Moreover, if vessel diameter and height is changing, the unit cost is scaled against the vessel volume.

Similar to the adsorber vessels, accounts 15.4 and 15.5 present system costs that will be directly aligned with the number of adsorber vessels considered. In cases where the number of units change but all other operating conditions are unchanged, the new number of units is simply multiplied by the unit cost. In cases where the operating conditions change (different air flow rate or pressure drop, e.g.), the unit costs are first adjusted based on the new operating conditions and then applied to the number of units. For Account 15.5, if only pressure drop experiences a change, the unit cost of the air handling fans can be scaled against the pressure drop, otherwise the fan cost should be scaled against the unit air fan auxiliary load. The balance of sub-accounts in Account 15 (15.2, 3, 6, 7, 8, and 9) were scaled using the recommended parameter and exponent for most other alternate system configurations.

Although Case 0B applies a monolithic sorbent structure, the cost estimate for the adsorber vessels were developed using the vessel cost estimate in Case 0 as a starting point. While the vessel diameter in Case 0B remained constant at 60 feet, as was applied in Case 0, the vessel bed depth in Case 0B is now 2 feet, as compared to the 5-foot depth in Case 0. This necessitated a scaling of the vessel unit cost on total vessel volume. The Case 0 vessel unit cost was $476,011 (BEC) per vessel, with a vessel volume of 14,137 ft^3. For Case 0B, the new vessel volume was calculated to be 5,655 ft^3. Scaling the unit cost on vessel volume with an exponent of 0.6 resulted in a new vessel unit cost of $274,697 (BEC) per vessel, or a total BEC of $5.49 M. Similarly, the change in system pressure drop resulting from the application of the monolith structure necessitated an alternate scaling approach for the air fans. These costs were scaled on auxiliary load per fan, using a 0.8 exponent.

Exhibit 5-15. Scaling parameters for DAC-specific equipment

Account Number	Item Description	Parameter	Exponent	Range
15	**Direct Air Capture System**			
15.1	DAC Adsorption/Desorption Vessels[A]	Vessel Internal Diameter, ft Vessel Internal Volume, ft^3	0.60	20–90 1,600–32,000
15.2	DAC CO_2 Compression & Drying	Compressor Auxiliary Load, kW	0.41	15,000–50,000
15.3	DAC CO_2 Compressor Aftercooler	Heat Exchanger Duty, MMBtu/hr	0.83	1–10
15.4	DAC System Air Handling Duct and Dampers	Inlet Air Flow, lb/hr	0.80	60,000,000–150,000,000
15.5	DAC System Air Handling Fans[A]	Pressure Drop, in. H_2O (differential) Air Fan Auxiliary Load, kW	0.80	10–50 45,000–180,000
15.6	DAC Desorption Process Gas Handling System	DAC CO_2 Product Flow Rate, lb/hr	0.60	20,000–60,000
15.7	DAC Steam Distribution System	DAC Steam Flow Rate, lb/hr	0.70	100,000–190,000
15.8	DAC System Controls Equipment	Total DAC Auxiliary Load, kW	0.15	50,000–120,000
15.9	Electric Boiler (Case 0-EB)	Feedwater Flow, lb/hr	0.8	45,000–70,000

[A] As described in the text, depending on the alternate case considered, application of the unit costs for a new number of units may be more appropriate. When dimensions and equipment parameters change as a result of alternate cases, new unit costs should be scaled using this guidance, and then multiplied by the number of units for that case.

5.3.2 Cost of CO_2 Capture Results

Using the methodology presented in Section 3.6, Exhibit 5-16 presents the results for the COC for Case 0B.

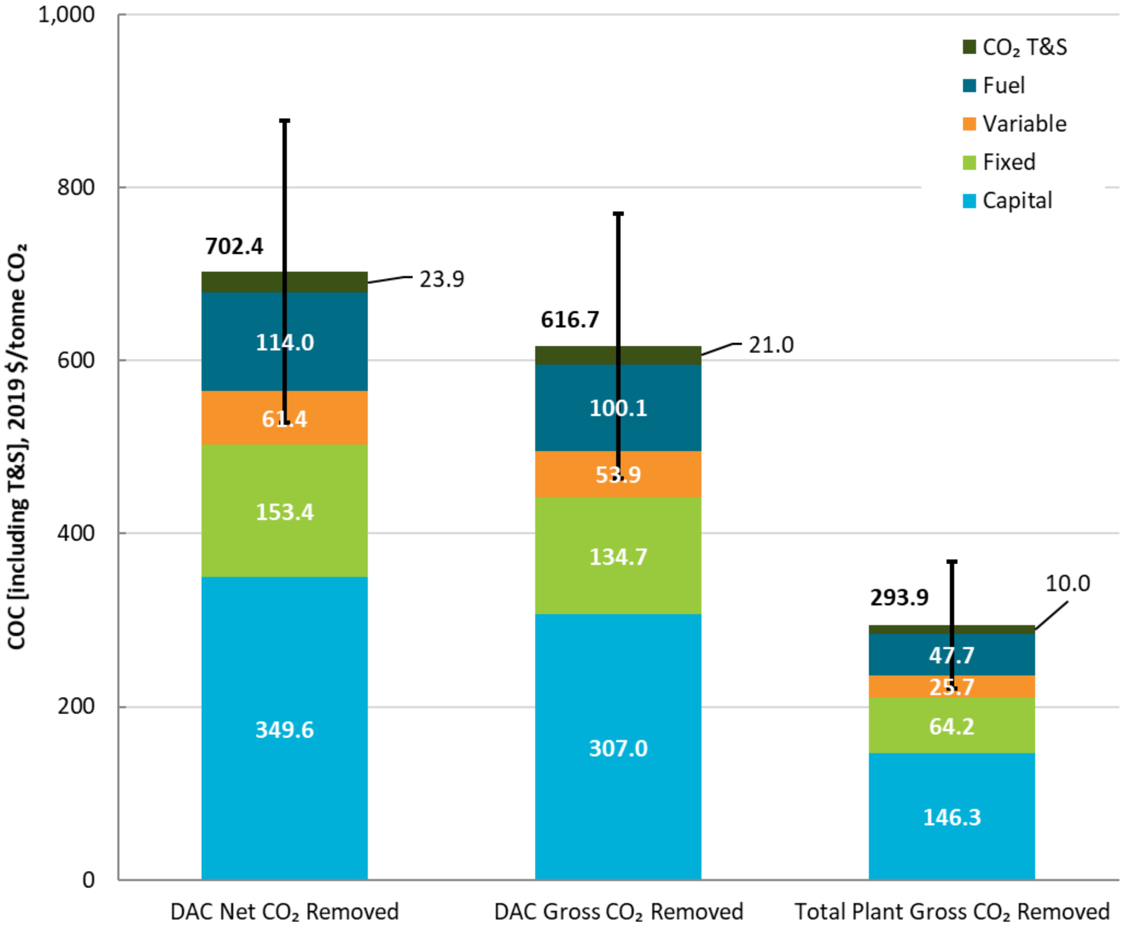
Exhibit 5-16. Case 0B COC reported in 2019 dollars

Component	COC DAC_{net}, $/tonne	COC DAC_{gross}, $/tonne	COC $Plant_{gross}$, $/tonne
Capital	349.6	307.0	146.3
Fixed	153.4	134.7	64.2
Variable	61.4	53.9	25.7
Fuel	114.0	100.1	47.7
Total (Excluding T&S)	**678.5**	**595.7**	**283.9**
CO_2 T&S	23.9	21.0	10.0
Total (Including T&S)	**702.4**	**616.7**	**293.9**

For the COC DAC_{net} result of $702/tonne CO_2 ($637/ton CO_2) (including T&S), a total CO_2 flow of 100,000 tonnes/yr (110,230 tons CO_2/yr) is used. For the COC DAC_{gross} result of $617/tonne CO_2 ($560/ton CO_2) (including T&S), a total CO_2 flow of 113,900 tonnes/yr (125,550 tons/yr) is used. For the COC $Plant_{gross}$ result of $294/tonne CO_2 ($267/ton CO_2) (including T&S), a total CO_2 flow of 238,990 tonnes/yr (263,440 tons/yr) is used, which represents the gross CO_2 captured by the DAC system from the atmosphere (113,900 tonnes/yr) plus the CO_2 captured by Shell's Cansolv system from the NGCC plant flue gas (125,090 tonnes/yr).

Exhibit 5-17 presents the COC results graphically and includes error bars relating to the uncertainty in the capital cost estimate. As highlighted previously, the capital estimates represent AACE Class 5 estimates, with an uncertainty range of +/-50 percent. The COC ranges presented are not reflective of other changes, such as variation in fuel price, O&M labor price, CF, or other factors. Note that many cost and performance assumptions for Case 0B are fairly optimistic and could result in a best-case COC. This includes the optimized layout, the low sorbent cost, and optimistic financial assumptions.

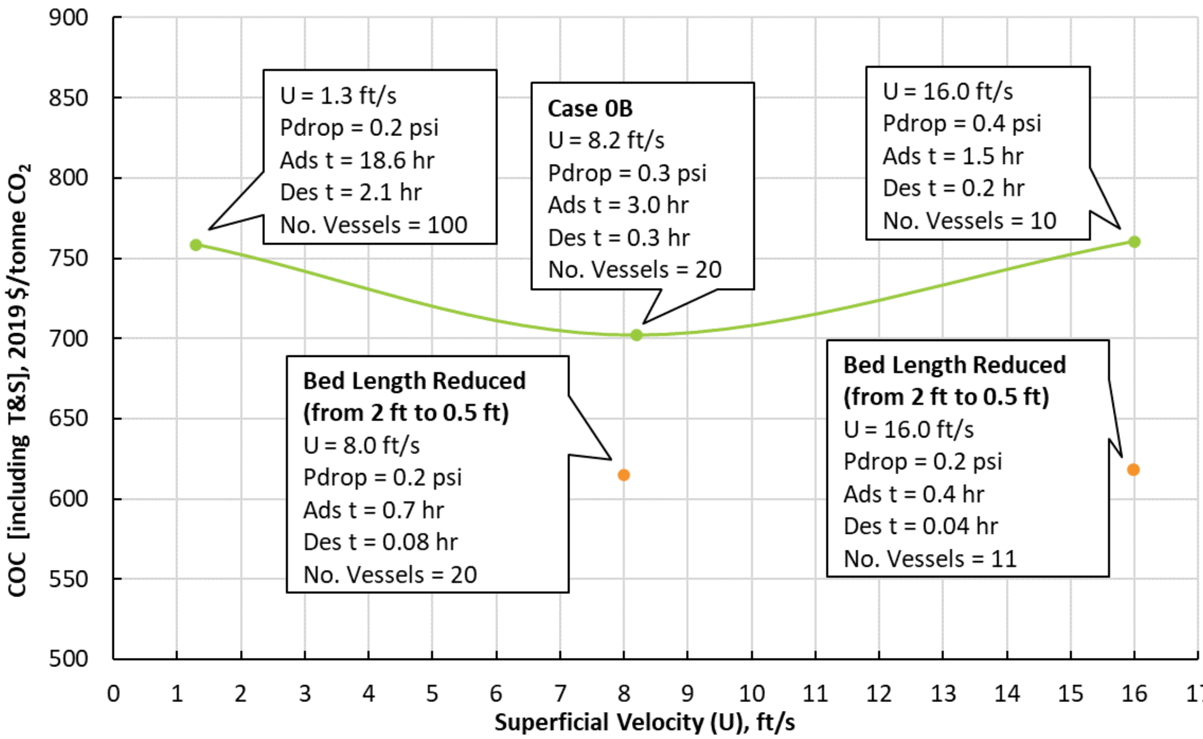
Exhibit 5-17. Case 0B COC plot and uncertainty ranges



5.3.3 Alternate Sorbent Support Configurations

As new and improved support materials for DAC applications continue to be reported in the literature, it is expected that the base assumptions for Case 0B will be exceeded resulting in further reductions in the overall CO_2 capture cost. To this end, additional sensitivity studies evaluating higher superficial velocities and shallower bed depths were considered, with the results plotted in Exhibit 5-18.

Exhibit 5-18. Case 0B sensitivity to superficial velocity and bed depth



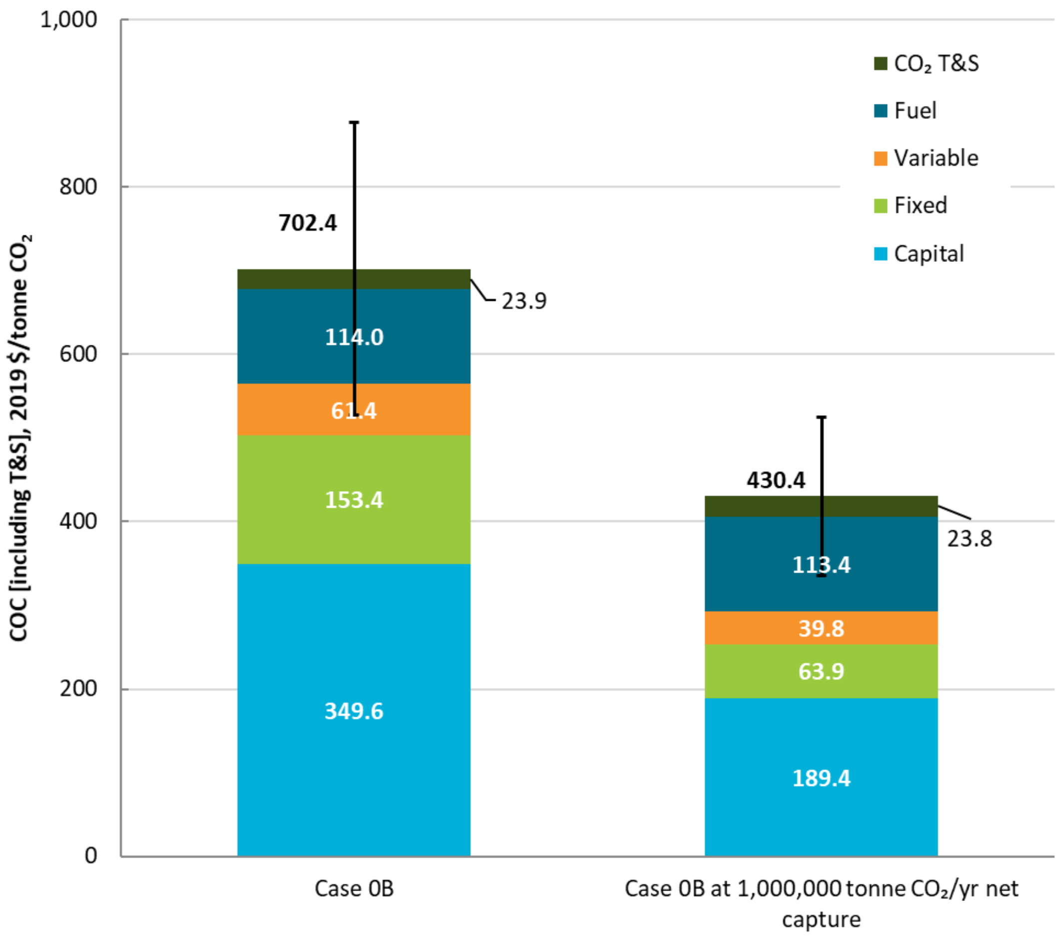
Case 0B considered a superficial velocity of 8.18 ft/s, with a sorbent bed depth of 2 feet, resulting in a system pressure drop of 0.3 psi. To achieve the target gross/net CO_2 removed from the atmosphere, the sorbent needs to cycle through adsorption in 3 hours, and desorption in 18 minutes. Increasing the superficial velocity to 16 ft/s negatively impacts the pressure drop and would require the material to cut its operational cycle times in half. This also results in an increase in the COC.

If a material were developed that was capable of operating with cycle times of approximately 42 minutes for adsorption and approximately 5 minutes for desorption, then the bed depth could be reduced from 2 feet to 6 inches using a superficial velocity of 8 ft/s, which would reduce the overall system pressure drop to 0.2 psi. The COC would then reduce from the Case 0B value of \$702/tonne CO_2 DAC_{net}, to \$615/tonne CO_2 DAC_{net}, when targeting a net system removal of 100,000 tonnes CO_2/year. Similar to the Case 0B result, when superficial velocity is increased for this case to 16 ft/s, the sorbent cycle times must reduce further (24 minutes and 2 minutes, respectively), and the COC result increases slightly.

5.3.4 Case 0B Scale Sensitivity

As highlighted in Section 3.4, the most common industrial DAC plant scale proposed in the literature appears to be 1 M tonnes CO_2 removed/yr. For the purposes of this study, the 2018 45Q tax credit threshold of 100,000 tonnes CO_2/year was selected as the target DAC scale due to the relative immaturity of these technologies, and unknowns regarding scale-up. However, it is recognized that selection of this target scale introduces dis-economies of scale into the results, making cross comparisons of results difficult. Therefore, Case 0B was scaled-up to the 1 M tonnes CO_2 removed/yr net capture rate to highlight the impacts of plant scale. The result of this scale sensitivity is shown in Exhibit 5-19. As shown, increasing the plant capacity from 100,000 tonnes CO_2/yr-net to 1 M tonnes CO_2/yr-net reduces the COC by 39 percent, from \$702/tonne CO_2 DAC_{net} to \$430/tonne CO_2 DAC_{net}.

Exhibit 5-19. Scale sensitivity to Case 0B



The scale sensitivity did not build upon the sorbent material sensitivity results presented in Section 5.3.3. It would be expected that as advancements in material performance are made, the COC of the monolith case at 1 M tonnes CO_2/yr-net would further reduce below the values presented.

5.3.5 Sensitivity Analysis

Due to the lack of publicly available literature regarding sorbent DAC systems, sensitivity analysis was conducted on multiple process and cost parameters to gauge their impact on the final system performance and COC. The parameters of interest include capital cost (presented in Section 5.3.2), natural gas price, sorbent cost, sorbent lifetime, financing assumptions (FCR), system capture fraction, sorbent regeneration energy, CF, and a single case addressing CO_2

product purity from the adsorber vessels. Impacts of system pressure drop were independently considered in the prior section for advanced support materials.

Exhibit 5-20 shows the COC sensitivity to natural gas price for the three different bases of calculation (DAC_{net}, DAC_{gross}, and Total $Plant_{Gross}$). The natural gas price is varied over the range of \$0.95/GJ (\$1/MMBtu—77 percent reduction from the reference) to \$9.5/GJ (\$10/MMBtu—126 percent increase from the reference). The results show that at the low natural gas price point, COC is reduced by 13 percent versus the reference, whereas, at the high natural gas price point, COC increases by 20 percent versus the reference. Fuel price accounts for approximately 16 percent of the COC (including T&S); therefore, COC is not overly sensitive to the price of natural gas.

Exhibit 5-20. COC sensitivity to natural gas price

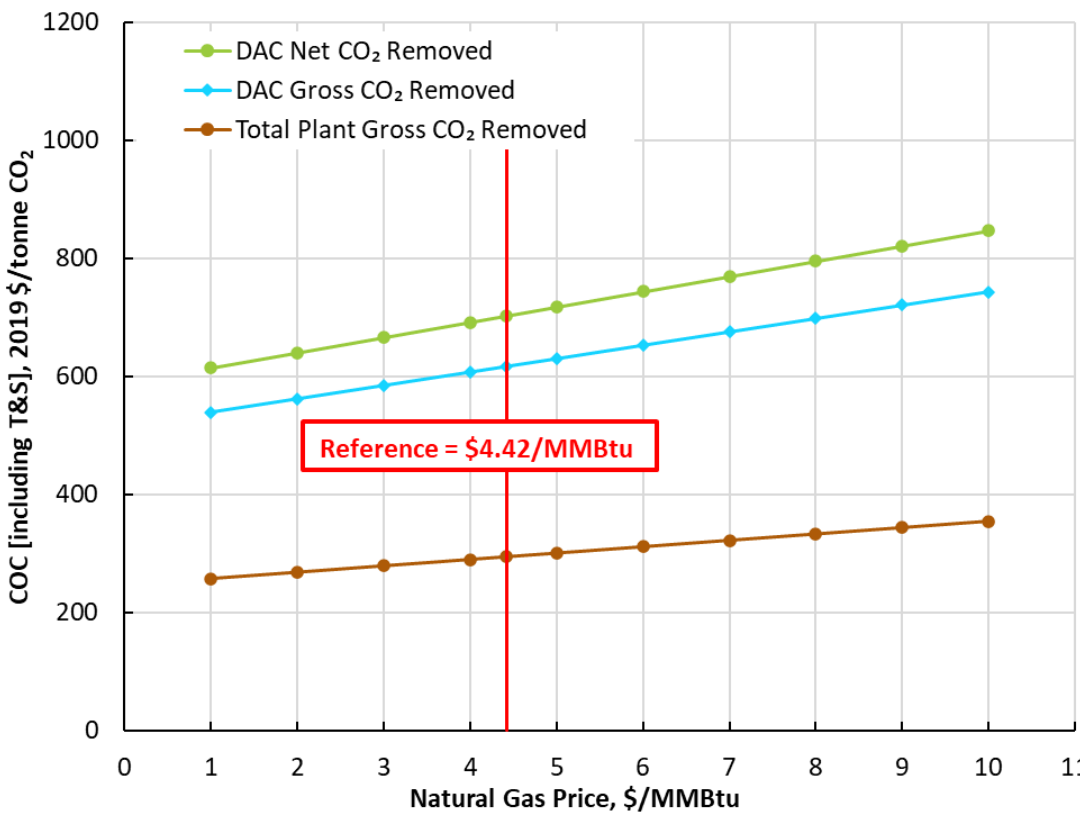


Exhibit 5-21 shows the COC sensitivity to sorbent cost for the three different bases of calculation. Due to lack of data, there was limited information available to inform the Case 0B assumption of \$4.0/ft^3 (\$0.09/lb) sorbent cost. Black & Veatch recommended the generic value of \$4.0/ft^3 (\$0.09/lb) for the baseline sorbent cost to reflect a generic cost for sorbents used commercially. A sorbent cost range spanning the literature reported values up to \$100/kg (\$2,000/ft^3) is considered. Assuming a sorbent cost within the literature reported range, the COC increases from \$702/tonne CO_2 to between \$1,030/tonne CO_2 for a sorbent price of \$15/kg and \$2,910/tonne CO_2 for a sorbent price of \$100/kg. The assumption that NOAK sorbent prices will be significantly lower than those reported in literature imparts a significant cost reduction.

Exhibit 5-21. COC sensitivity to sorbent cost

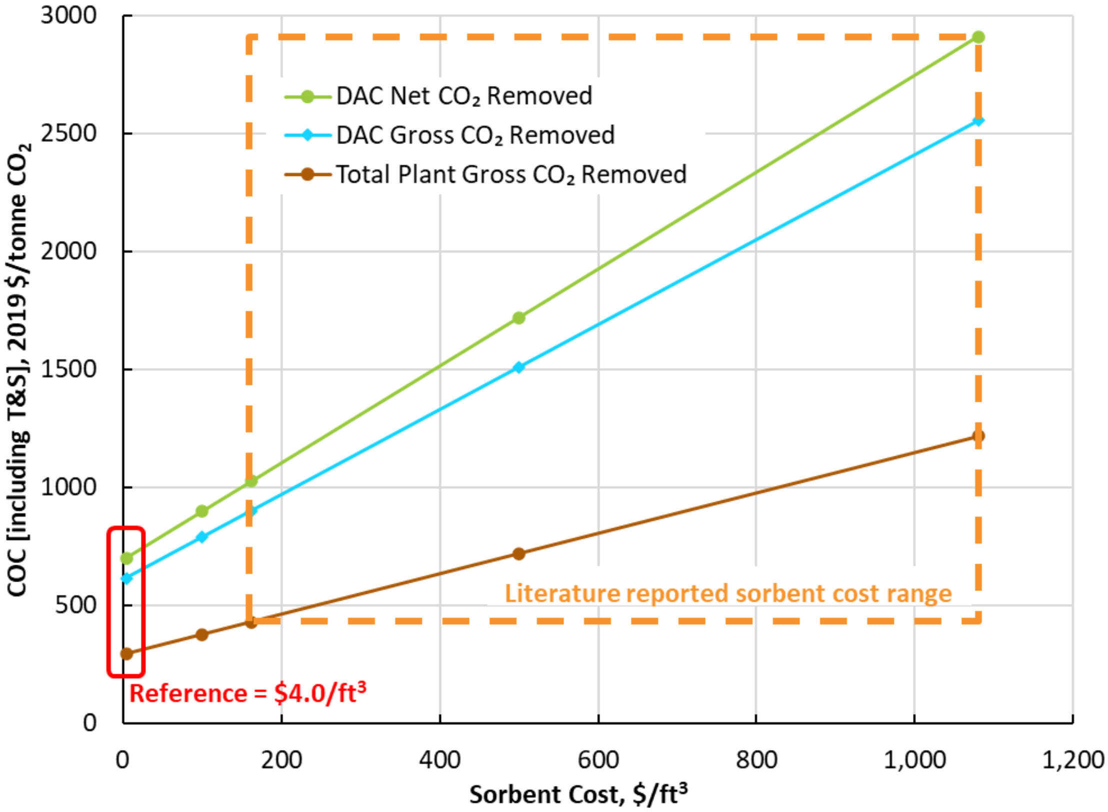


Exhibit 5-22 shows the COC sensitivity to sorbent lifetime for the three different bases of calculation. Case 0B assumes that the sorbent life is 6 months. Due to lack of data, there was limited information available to inform this assumption. The sensitivity range is -50 percent (3 months) to +900 percent (5 years), and the COC shows about a 1 percent increase or decrease at the endpoints of this range. At a sorbent lifetime of approximately 2 years, the COC trend begins to level out, with minimal reductions in COC as the sorbent lifetime extends from 2 years to 5 years. This trend will be more pronounced and will shift assuming higher sorbent costs.

Exhibit 5-22. COC sensitivity to sorbent lifetime

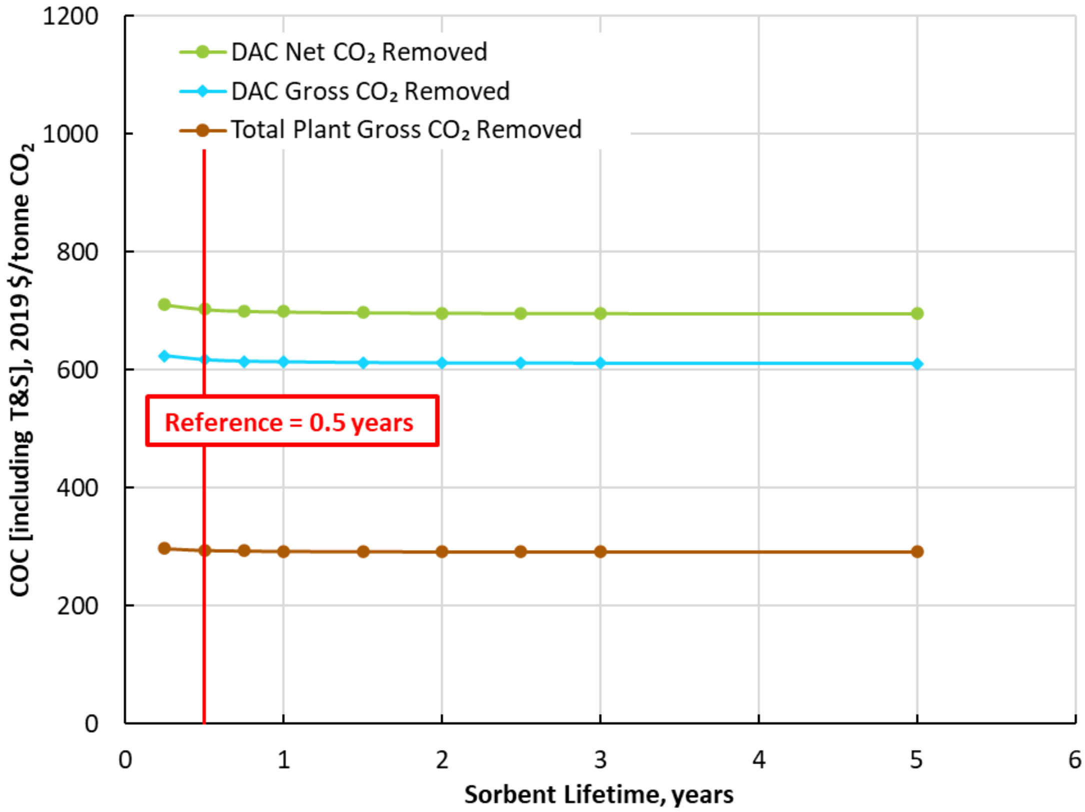


Exhibit 5-23 shows the COC sensitivity to FCR for the three different bases of calculation. Case 0B assumes an FCR of 0.07, which is the value used for NGCC plant levelized cost of electricity (LCOE) calculations as discussed in Section 3.6. This value was selected based on its assumed three-year construction period. The importance of this sensitivity study is that the base FCR assumption is already favorably low for Case 0B, and alternate financial parameter assumptions may result in an FCR that is higher than the base assumption. In this case, the COC will increase, and given the slope of the lines in Exhibit 5-23, the resulting COC could be significantly higher than Case 0B. Doubling the FCR would result in approximately a 50 percent increase in the COC.

As will be outlined in Section 8, alternate cases should be considered where financial parameters consistent with the chemical industry are selected, and a new FCR and COC can be calculated.

Exhibit 5-23. COC sensitivity to fixed charge rate

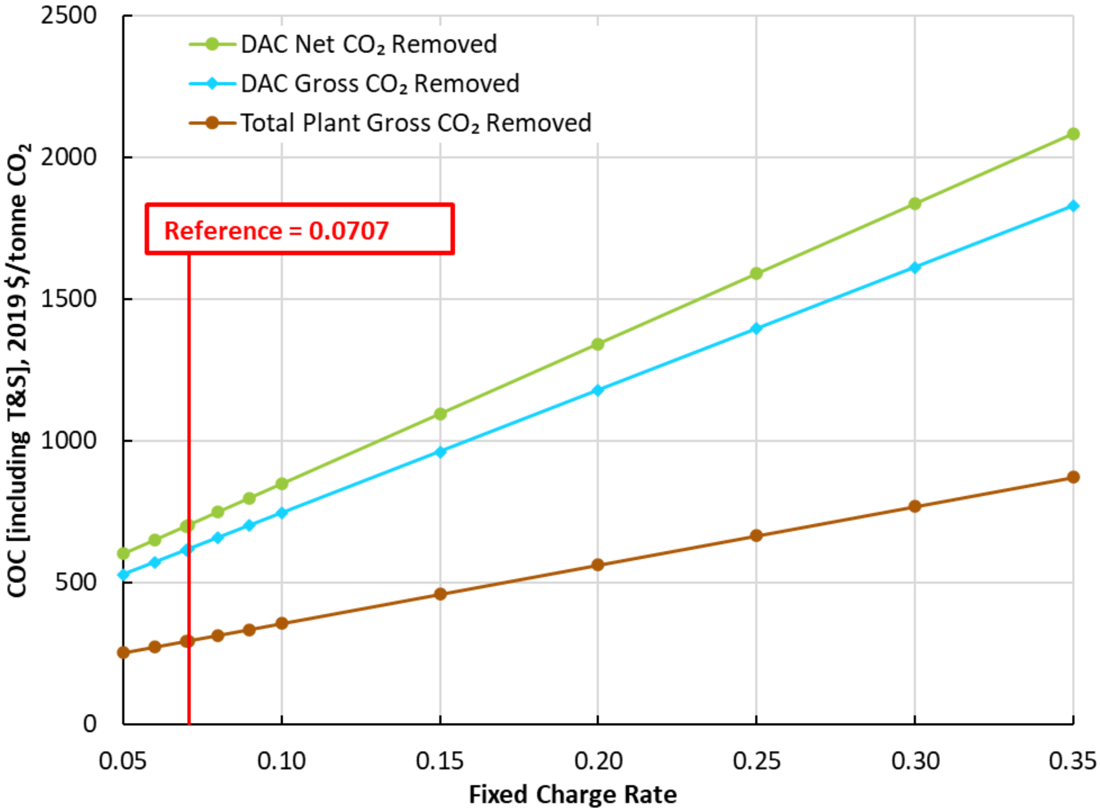


Exhibit 5-24 shows the COC sensitivity to DAC system capture fraction for the three different bases of calculation. Case 0B assumes that the DAC adsorbers remove 60 percent of the inlet CO_2 present in the air, and this value was selected based on the target capture rates presented in the literature. As expected, as the amount of CO_2 removed increases, and the denominator of the COC calculation increases, the total COC decreases. For perspective, at a capture rate of 30 percent, 390,290 tonnes/yr (430,221 tons/yr) of CO_2 must be captured from the combination of the DAC plant and Shell's Cansolv CO_2 capture system to achieve a net removal from the atmosphere of 100,000 tonnes/yr (110,230 tons/yr). As stated earlier, Case 0B requires that a total of 238,990 tonnes/yr (263,441 tons/yr) be captured. At a capture rate of 90 percent by the DAC adsorbers, a total of only 207,220 tonnes/yr (228,421 tons/yr) must be removed to achieve the target net atmospheric removal. The COC calculated at 90 percent removal is $584/tonne CO_2 ($530/ton CO_2), a 17 percent reduction from Case 0B.

Exhibit 5-24. COC sensitivity to capture fraction

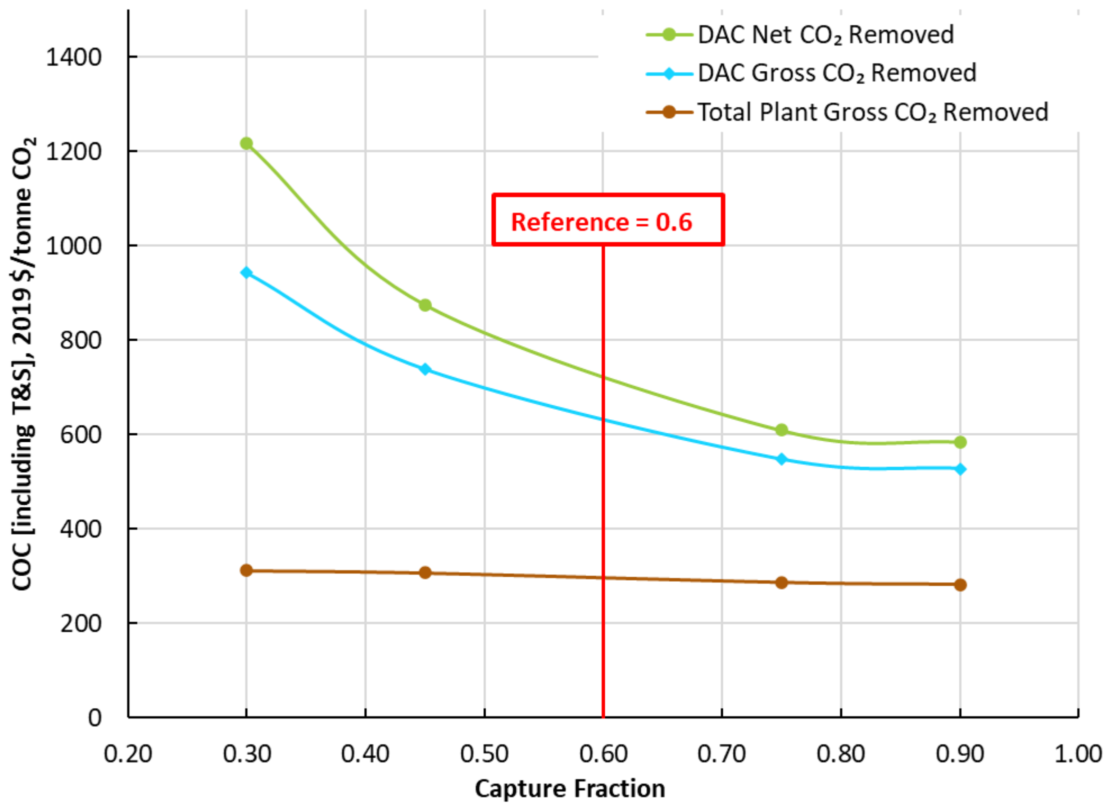


Exhibit 5-25 shows the COC sensitivity to DAC sorbent regeneration energy for the three different bases of calculation. Case 0B assumes a sorbent regeneration energy of 4.3 GJ/tonne CO_2 (1,847 Btu/lb CO_2), and this value was selected based on data presented in the literature for sorbent regeneration energy. As shown, the COC result is not particularly sensitive to sorbent regeneration energy, but sensitivity appears to increase as regeneration energy rises above 2,300 Btu/lb CO_2. A sensitivity range of +/- 50 percent results in a 7 percent increase and a 3 percent decrease in the COC, respectively.

Exhibit 5-25. COC sensitivity to sorbent regeneration energy

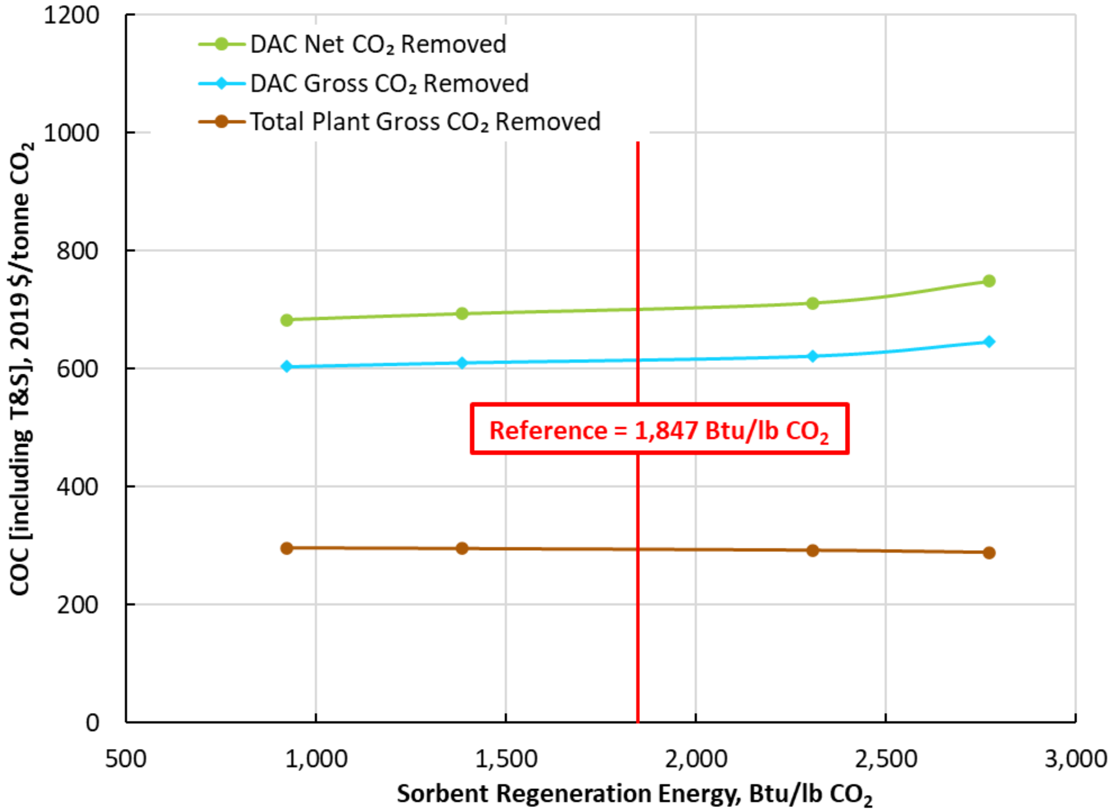
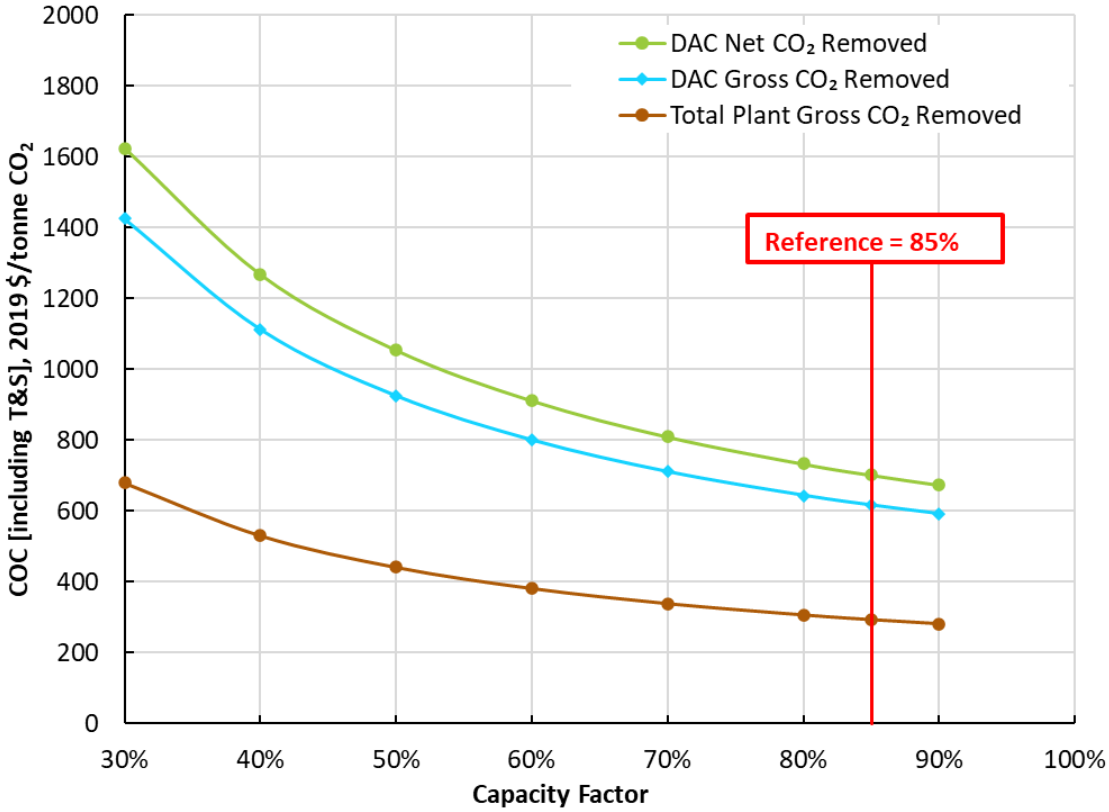


Exhibit 5-26 shows the COC sensitivity to DAC system CF for the three different bases of calculation. Case 0B assumes a CF of 85 percent. As expected, as the CF of the DAC plant reduces, the COC increases rapidly, indicating that high CFs will be required for a DAC plant to be economically competitive.

Exhibit 5-26. COC sensitivity to CF



The final sensitivity case considered examines the purity of the CO_2 product coming from the DAC adsorber during the desorption phase. Case 0B assumes that the DAC CO_2 product is 100 percent pure CO_2 leaving the adsorber and entering the CO_2 compressor. There was limited information available in the literature regarding raw DAC product CO_2 purity leaving the adsorber vessels, with most references suggesting that the compressed CO_2 product leaving the DAC plant would be highly pure, or at a minimum, meet CO_2 pipeline specifications. Since the sorbent considered in this case study is represented as a generic sorbent, parameters such as void fraction represent unknowns. Therefore, it is difficult to determine how much residual air may be present in each adsorber when the system switches phases from adsorption to desorption, and how the air trapped in the void space, or how air components potentially adsorbed to the sorbent surface, would impact the final CO_2 product purity. Therefore, a single sensitivity case was considered where the DAC CO_2 compressor was removed and replaced with a cryogenic CO_2 purification and compression unit (CPU) unit.

The CPU data were sourced from a prior NETL report that examined advanced oxy-combustion technologies for coal-fired power plants. [30] Salient data for the CPU is presented in Exhibit A-29 in Appendix A: Reference Case 0.

Exhibit 5-27 presents the relevant cost comparison data for Case 0B and the low-purity CO_2 sensitivity case, as well as the final COC result. Application of the CPU capital cost maintained the same process and project contingencies that were assumed in the reference report, and the same engineering home office and fee percentage that has been applied to the DAC system in this study.

Exhibit 5-27. COC result for Case 0B (high-purity CO_2) versus a low-purity CO_2 case

Component	Case 0B	Low-Purity CO_2 Case
DAC CO_2 Compressor and Aftercooler TPC, x1000 2019 $	5,487	-
Scaled CPU TPC, x1000 2019 $	-	21,310
Total Plant TOC, x1000 2019 $	452,349	478,088
Total Plant TOC, 2019 $/tonne CO_2 net	4,523	4,568
COC DAC_{net}, 2019 $/tonne	702	731
Percent Increase in COC, %	-	4.1

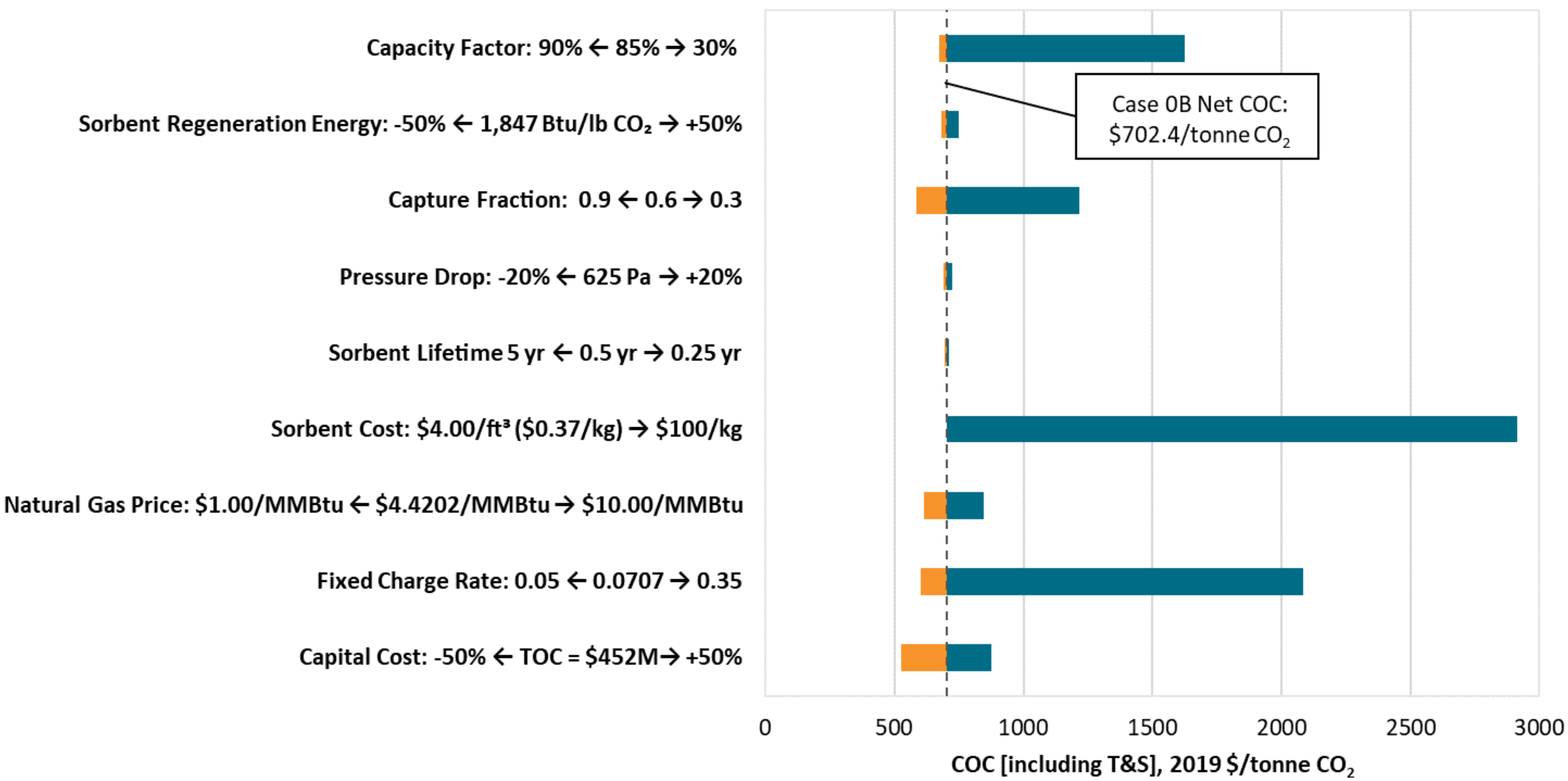
Replacement of the DAC CO_2 compressor with the CPU adds an additional $25.7 M to the TOC of the sensitivity case. However, given the high capital cost of the reference Case 0B, this value only represents approximately a 5.7 percent increase in the TOC, and results in a 4.1 percent increase in the COC.

The CPU cost applied in this sensitivity study inherently assumes a fixed inlet CO_2 purity, and if the DAC process were to provide a CO_2 product stream below this purity, the CPU capital cost, and COC result, would increase.

Exhibit 5-28 summarizes the sensitivity study results described in this section and plots the potential impacts such that the importance of different parameters can be weighed against each other.

Based on Case 0B assumptions, and the parameter sensitivity ranges assumed, for a 100,000 tonne/yr capture system, there is no sensitivity case presented that would independently allow the DAC system to achieve a COC_{net} below $500/tonne CO_2 ($454/tonne CO_2). However, the cumulative effect of multiple sensitivity parameters rolled into a single case could result in a COC_{net} below this threshold for the base Case 0B. This does not account for the larger scale case, presented previously, which resulted in a COC below $500/tonne CO_2. Many of the parameters assumed in Case 0B (e.g., FCR, pressure drop, capture fraction) could be viewed as optimistic assumptions that position Case 0B to have a best-case COC outcome. Further investigation into these and other system parameters is required to better refine the COC results presented for Case 0B.

Exhibit 5-28. Summary of Case 0B COC sensitivity results



6 CASE 0B-EB – ELECTRIC BOILER

Case 0B-EB considers the same DAC system as Case 0B, with the exception of the power and steam generation sub-systems. Case 0B-EB utilizes an electric boiler to produce the steam needed for the thermal regeneration of the CO_2 adsorbent. It is assumed that the electricity required to satisfy the auxiliary load for the reference Case 0B-EB is purchased at a sale price of $60/MWh. This purchase price represents the average price of electricity from the grid based on output from the National Energy Modeling System by Census Region and the West North Central region for 2023–2050. The emission profile, or carbon footprint, of the purchased electricity is not considered in this analysis as only emissions within the plant bounds are quantified. However, it is reasoned that the electricity required for this scenario will need to be low carbon to facilitate a truly negative-emissions system and will likely need to be provided by renewable sources. To gauge the impact of different renewable electricity sources, sensitivities were conducted on CF and the price of purchased electricity. In this case, it is assumed that purchased electricity has no process-related CO_2 emissions, such that the gross capture rate of the DAC system, at 100,000 tonnes CO_2/yr (110,230 tons/yr), is equal to the net capture rate.

In this section, the Case 0B-EB system is described. The system description follows the BFD in Exhibit 6-1 and stream numbers reference the same exhibit. Exhibit 6-2 provides process data for the numbered streams in the BFD.

Exhibit 6-1. Case 0B-EB BFD, sorbent-based DAC system

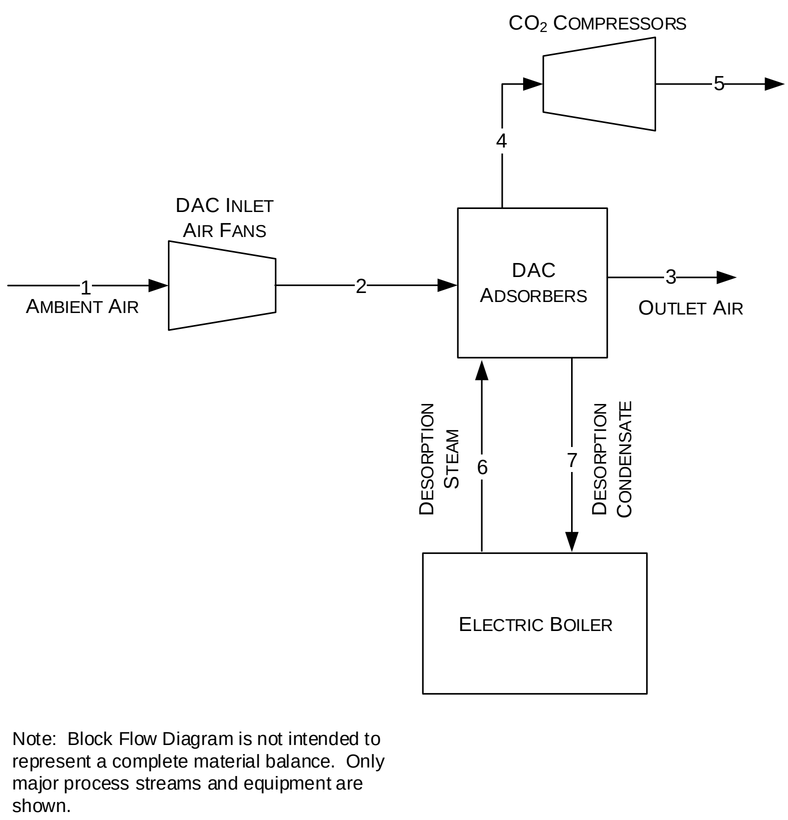


Exhibit 6-2. Case 0B-EB stream table, sorbent-based DAC system

	1	2	3	4	5	6	7
V-L Mole Fraction							
Ar	0.0092	0.0092	0.0092	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0004	0.0004	0.0002	1.0000	1.0000	0.0000	0.0000
H_2O	0.0101	0.0101	0.0101	0.0000	0.0000	1.0000	1.0000
N_2	0.7724	0.7724	0.7726	0.0000	0.0000	0.0000	0.0000
O_2	0.2079	0.2079	0.2079	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	1,251,087	1,251,087	1,250,782	305	305	1,462	1,462
V-L Flowrate (kg/hr)	36,102,230	36,102,230	36,088,800	13,430	13,430	26,339	26,339
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0
Temperature (°C)	15	18	18	100	30	153	138
Pressure (MPa, abs)	0.10	0.10	0.10	0.10	15.27	0.51	0.49
Steam Table Enthalpy (kJ/kg)[A]	30.65	33.52	33.53	86.50	-231.33	2,773.62	575.70
Aspen Plus Enthalpy (kJ/kg)[B]	-100.93	-98.06	-94.76	-8,875.57	-9,193.41	-13,197.72	-15,456.25
Density (kg/m³)	1.2	1.2	1.2	1.5	628.8	2.7	877.4
V-L Molecular Weight	28.857	28.857	28.853	44.010	44.010	18.015	18.015
V-L Flowrate (lb-mol/hr)	2,758,176	2,758,176	2,757,503	673	673	3,223	3,223
V-L Flowrate (lb/hr)	79,591,793	79,591,793	79,562,185	29,608	29,608	58,068	58,068
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0
Temperature (°F)	59	64	64	212	86	308	280
Pressure (psia)	14.7	15.1	14.8	14.8	2,214.7	73.5	70.6
Steam Table Enthalpy (Btu/lb)[A]	13.2	14.4	14.4	37.2	-99.5	1,192.4	247.5
Aspen Plus Enthalpy (Btu/lb)[B]	-43.4	-42.2	-40.7	-3,815.8	-3,952.5	-5,674.0	-6,645.0
Density (lb/ft³)	0.076	0.077	0.076	0.091	39.252	0.166	54.774

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

6.1 Case 0B-EB – Process Description and Performance Results

Case 0B-EB captures a net 100,000 tonnes CO_2/yr (110,230 tons/yr) from the atmosphere. Purchased power is required to satisfy plant auxiliary loads, and it is assumed that electricity is provided by renewable sources with negligible associated CO_2 emissions for a price of $60/MWh.

Ambient air (stream 1) is sent through fans and a duct system to distribute air to the DAC adsorber vessels (stream 2). During steady-state operations, 90 percent of the vessels will be operating in adsorption mode (3-hour cycle) and receiving air from the fans. The remaining adsorption vessels will be in desorption mode (0.3-hour cycle) and utilize steam from the electric boiler (stream 6) to drive CO_2 from the sorbent. The electric boiler produces steam at

308°F (153°C) and 73.5 psia. The product CO_2 is pulled from the adsorber vessels to the CO_2 compressor (stream 4), where it is compressed to 15.2 MPa (2,200 psig) (stream 5).

Overall plant performance is summarized in Exhibit 6-3; Exhibit 6-4 provides a detailed breakdown of the auxiliary power requirements.

Exhibit 6-3. Case 0B-EB plant performance summary

Performance Summary	
Total Gross Power, MWe	**0**
DAC Air Fans, kWe	28,800
DAC CO_2 Compression, kWe	1,490
Electric Boiler, kWe	19,510
Balance of Plant, kWe	163
Total Auxiliaries, MWe	**50**
Net Power, MWe	**-50**
DAC CO_2 Removed from Air (Gross), tonnes/yr	100,000
Net CO_2 Removed from Air, tonnes/yr	**100,000**

Exhibit 6-4. Case 0B-EB plant power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Circulating Water Pumps, kWe	70
Cooling Tower Fans, kWe	40
Feedwater Pumps, kWe	2
Ground Water Pumps, kWe	10
Miscellaneous Balance of Plant,[A] kWe	41
Air Fans, kWe	28,800
Electric Boiler, kWe	19,510
CO_2 Compression, kWe	1,490
Total Auxiliaries, MWe	**50**
Net Power, MWe	**-50**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

6.1.1 Environmental Performance

Case 0B-EB utilizes an electric boiler for steam requirements and assumes renewable electricity is purchased to satisfy plant auxiliary load. Because the renewable electricity purchased by the plant is assumed to have negligible associated process emissions, this case reports no air emissions of SO_2, NOx, PM, Hg, CO, or CO_2.

The carbon balance for the plant is shown in Exhibit 6-5. The carbon input to the plant consists of carbon in the air fed to the DAC adsorber vessels. Carbon leaves the plant as CO_2 through the DAC vessels and DAC CO_2 product stream.

Exhibit 6-5. Case 0B-EB carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
DAC Air (CO_2)	6,109 (13,468)	DAC CO_2	3,665 (8,081)
	–	DAC Vessel	2,444 (5,387)
Total	**6,109 (13,468)**	**Total**	**6,109 (13,468)**

Exhibit 6-6 shows the overall water balance for Case 0B-EB.

Exhibit 6-6. Case 0B-EB water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
Deaerator	–	–	–	0.0 (12)	0.0 (-12)
BFW Makeup	0.0 (13)	–	0.0 (13)	–	0.0 (13)
Cooling Tower	0.3 (73)	0.0 (1.0)	0.3 (72)	0.1 (16)	0.2 (55)
BFW Blowdown	–	0.0 (1.0)	0.0 (-1.0)	–	0.0 (-1.0)
Total	**0.3 (85)**	**0.0 (1.0)**	**0.3 (84)**	**0.1 (28)**	**0.2 (56)**

6.1.2 Energy Balance

An overall plant energy balance is provided in tabular form in Exhibit 6-7.

Exhibit 6-7. Case 0B-EB overall energy balance (0 °C [32 °F] reference)

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
DAC Air	–	1,106 (1,049)	–	1,106 (1,049)
Raw Water Makeup	–	1.2 (1.1)	–	1.2 (1.1)
Auxiliary Power	–	–	180 (170)	180 (170)
TOTAL	0.0 (0.0)	1,108 (1,050)	180 (170)	1,287 (1,220)
Heat Out GJ/hr (MMBtu/hr)				
DAC Stack Gas	–	1,210 (1,147)	–	1,210 (1,147)
Motor Losses and Design Allowances	–	–	0.0 (0.0)	0.0 (0.0)
Cooling Tower Load[A]	–	36 (34)	–	36 (34)
Blowdown	–	0.0 (0.0)	–	0.0 (0.0)
DAC CO_2 Product Stream	–	-3.1 (-2.9)	–	-3.1 (-2.9)
Ambient Losses[B]	–	*0.3 (0.3)*	–	*0.3 (0.3)*
Power	–	–	0.0 (0.0)	0.0 (0.0)
TOTAL	–	1,243 (1,178)	0.0 (0.0)	1,243 (1,178)
Unaccounted Energy[C]	–	*44 (42)*	–	*44 (42)*

[A]Includes the CO_2 compressor and miscellaneous cooling loads
[B]Ambient losses include all losses to the environment through radiation, convection, etc.
[C]By difference

The cooling tower load includes the CO_2 compressor intercooler load and other miscellaneous cooling loads.

6.2 Case 0B-EB – Cost Estimate Results

Exhibit 6-8 shows a detailed breakdown of the capital costs; Exhibit 6-9 shows the owner's costs, TOC, and TASC; Exhibit 6-10 shows the initial and annual O&M costs; and Exhibit 6-11 shows the COC breakdown.

The uncertainty of the capital cost estimates is +/-50 percent, consistent with Association for the Advancement of Cost Engineering (AACE) Class 5 cost estimates (i.e., concept screening), based on the level of engineering design performed. In all cases, this report relies on vendor cost estimates for component technologies and process equipment, corresponding to the assumption- and/or model-derived equipment specifications. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs, which can be a challenge for emerging technologies.

Estimates were developed on a NOAK basis; i.e, all cost estimates were intended to reflect the cost reduction that would be seen after widespread technology deployment. Cost premiums that would be expected for first-of-a-kind technologies (e.g., various sorbent materials) are not reflected in the cost estimates. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required. All costs are reported in 2019 dollars.

Sorbent-based direct air capture (DAC) systems are an immature technology, lacking a history of commercial deployment at scale. The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher the presented estimates. Absent demonstrated first-of-a-kind (FOAK) plant costs associated with a specific plant configuration/technology, it is difficult to explicitly project fully mature, N^{th}-of-a-kind (NOAK) values. Consequently, the cost estimates provided herein represent neither FOAK nor NOAK costs. Nevertheless, the application of a consistent methodology - and the presentation of detailed equipment specifications and costs based on contemporary sources - facilitate comparison between cases as well as sensitivity analyses to guide R&D, and generally improve upon many publicly available estimates characterized by more opaque methods and sources, and less detail.

Anticipated actual costs for projects based upon any of the cases presented herein 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 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.

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 here.

Exhibit 6-8. Case 0B-EB total plant cost details

Case:		DAC-0B-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
1	Sorbent Handling										
1.5	Sorbent Receive & Unload	$12	$0	$3	$0	$15	$3	$0	$3	$21	$0
1.6	Sorbent Stackout & Reclaim	$93	$0	$17	$0	$110	$22	$0	$20	$151	$2
1.7	Sorbent Conveyors	$135	$29	$33	$0	$196	$39	$0	$35	$271	$3
1.8	Other Sorbent Handling	$7	$2	$4	$0	$12	$2	$0	$2	$16	$0
1.9	Sorbent Handling Foundations	$0	$95	$125	$0	$220	$44	$0	$40	$303	$3
	Subtotal	$246	$126	$181	$0	$553	$111	$0	$99	$763	$8
2	Sorbent Preparation and Feed										
2.5	Sorbent Preparation Equipment	$60	$3	$12	$0	$75	$15	$0	$13	$103	$1
2.6	Sorbent Storage & Feed	$100	$0	$38	$0	$138	$28	$0	$25	$190	$2
2.9	Sorbent Feed Foundation	$0	$41	$36	$0	$78	$16	$0	$14	$107	$1
	Subtotal	$160	$44	$86	$0	$290	$58	$0	$52	$401	$4
3	Feedwater and Miscellaneous BOP Systems										
3.1	Feedwater System	$206	$353	$177	$0	$736	$147	$0	$132	$1,015	$10
3.2	Water Makeup & Pretreating	$283	$28	$160	$0	$472	$94	$0	$113	$679	$7
3.3	Other Feedwater Subsystems	$117	$38	$36	$0	$192	$38	$0	$35	$265	$3
3.4	Service Water Systems	$86	$164	$531	$0	$781	$156	$0	$187	$1,125	$11
3.5	Other Boiler Plant Systems	$46	$17	$42	$0	$104	$21	$0	$19	$144	$1
3.7	Waste Water Treatment Equipment	$535	$0	$328	$0	$864	$173	$0	$207	$1,243	$12
	Subtotal	$1,273	$601	$1,274	$0	$3,148	$630	$0	$694	$4,472	$45
9	Cooling Water System										
9.1	Cooling Towers	$556	$0	$168	$0	$724	$145	$0	$130	$1,000	$10
9.2	Circulating Water Pumps	$77	$0	$5	$0	$81	$16	$0	$15	$112	$1
9.3	Circulating Water System Auxiliaries	$1,355	$0	$179	$0	$1,534	$307	$0	$276	$2,117	$21
9.4	Circulating Water Piping	$0	$256	$232	$0	$488	$98	$0	$88	$673	$7
9.5	Make-up Water System	$73	$0	$94	$0	$168	$34	$0	$30	$232	$2
9.6	Component Cooling Water System	$38	$0	$29	$0	$67	$13	$0	$12	$92	$1
9.7	Circulating Water System Foundations	$0	$59	$98	$0	$158	$32	$0	$38	$227	$2

Case:		DAC-0B-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	Subtotal	$2,099	$315	$805	$0	$3,220	$644	$0	$589	$4,453	$45
10	Spent Sorbent Handling System										
10.6	Spent Sorbent Storage Silos	$87	$0	$267	$0	$355	$71	$0	$64	$489	$5
10.7	Spent Sorbent Transport & Feed Equipment	$297	$0	$294	$0	$592	$118	$0	$106	$816	$8
10.9	Spent Sorbent Foundation	$0	$61	$75	$0	$135	$27	$0	$33	$195	$2
	Subtotal	$384	$61	$636	$0	$1,082	$216	$0	$203	$1,501	$15
11	Accessory Electric Plant										
11.1	Generator Equipment	$520	$0	$392	$0	$913	$183	$0	$164	$1,259	$13
11.2	Station Service Equipment	$1,286	$0	$110	$0	$1,396	$279	$0	$251	$1,927	$19
11.3	Switchgear & Motor Control	$1,836	$0	$319	$0	$2,154	$431	$0	$388	$2,973	$30
11.4	Conduit & Cable Tray	$0	$444	$1,278	$0	$1,722	$344	$0	$310	$2,376	$24
11.5	Wire & Cable	$0	$662	$1,184	$0	$1,846	$369	$0	$332	$2,548	$25
11.6	Protective Equipment	$31	$0	$108	$0	$140	$28	$0	$25	$193	$2
11.7	Standby Equipment	$167	$0	$154	$0	$322	$64	$0	$58	$444	$4
11.8	Main Power Transformers	$246	$0	$5	$0	$251	$50	$0	$45	$346	$3
11.9	Electrical Foundations	$0	$15	$38	$0	$53	$11	$0	$13	$76	$1
	Subtotal	$4,086	$1,121	$3,589	$0	$8,796	$1,759	$0	$1,586	$12,141	$121
12	Instrumentation and Control										
12.4	Other Major Component Control Equipment	$440	$0	$281	$0	$721	$144	$36	$135	$1,036	$10
12.5	Signal Processing Equipment	$390	$0	$12	$0	$402	$80	$0	$72	$554	$6
12.6	Control Boards, Panels & Racks	$97	$0	$59	$0	$156	$31	$8	$29	$225	$2
12.7	Distributed Control System Equipment	$5,396	$0	$165	$0	$5,561	$1,112	$278	$1,043	$7,995	$80
12.8	Instrument Wiring & Tubing	$446	$356	$1,426	$0	$2,228	$446	$111	$418	$3,202	$32
12.9	Other Instrumentation & Controls Equipment	$309	$0	$715	$0	$1,023	$205	$51	$192	$1,471	$15
	Subtotal	$7,078	$356	$2,657	$0	$10,091	$2,018	$484	$1,889	$14,483	$145
13	Improvements to Site										
13.1	Site Preparation	$0	$162	$3,441	$0	$3,603	$721	$0	$865	$5,188	$52
13.2	Site Improvements	$0	$521	$689	$0	$1,210	$242	$0	$290	$1,742	$17
13.3	Site Facilities	$500	$0	$525	$0	$1,025	$205	$0	$246	$1,476	$15
	Subtotal	$500	$683	$4,654	$0	$5,838	$1,168	$0	$1,401	$8,407	$84

Case:		DAC-0B-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	14	Buildings and Structures									
14.4	Administration Building	$0	$141	$95	$0	$236	$47	$0	$43	$326	$3
14.5	Circulation Water Pumphouse	$0	$3	$1	$0	$4	$1	$0	$1	$6	$0
14.6	Water Treatment Buildings	$0	$30	$28	$0	$58	$12	$0	$10	$80	$1
14.7	Machine Shop	$0	$205	$131	$0	$336	$67	$0	$61	$464	$5
14.8	Warehouse	$0	$167	$101	$0	$267	$53	$0	$48	$369	$4
14.9	Other Buildings & Structures	$0	$150	$108	$0	$258	$52	$0	$46	$356	$4
14.10	Waste Treating Building & Structures	$0	$281	$502	$0	$783	$157	$0	$141	$1,080	$11
	Subtotal	$0	$976	$966	$0	$1,943	$389	$0	$350	$2,681	$27
	15	Direct Air Capture System									
15.1	DAC Adsorption/Desorption Vessels	$0	$1,773	$1,450	$0	$3,223	$645	$322	$629	$4,819	$48
15.2	DAC Carbon Dioxide (CO_2) Compression & Drying	$1,858	$279	$771	$0	$2,908	$582	$291	$567	$4,347	$43
15.3	DAC Carbon Dioxide (CO_2) Compressor Aftercooler	$69	$11	$30	$0	$110	$22	$0	$20	$152	$2
15.4	DAC System Air Handling Duct and Dampers	$3,858	$15,431	$6,430	$0	$25,718	$5,144	$2,572	$5,015	$38,449	$384
15.5	DAC System Air Handling Fans	$22,107	$0	$1,164	$0	$23,271	$4,654	$2,327	$4,538	$34,790	$348
15.6	DAC Desorption Process Gas Handling System	$152	$647	$212	$0	$1,011	$202	$101	$197	$1,511	$15
15.7	DAC Steam Distribution System	$260	$1,110	$364	$0	$1,734	$347	$173	$338	$2,592	$26
15.8	DAC System Controls Equipment	$367	$0	$234	$0	$601	$120	$60	$117	$898	$9
15.9	Electric Boiler	$2,554	$0	$134	$0	$2,688	$538	$0	$484	$3,709	$37
	Subtotal	$31,225	$19,250	$10,789	$0	$61,263	$12,253	$5,847	$11,904	$91,267	$913
	Total	**$47,051**	**$23,533**	**$25,639**	**$0**	**$96,223**	**$19,245**	**$6,331**	**$18,768**	**$140,567**	**$1,406**

Exhibit 6-9. Case 0B-EB owner's costs

Description	$/1,000	$/tonne
Pre-Production Costs		
6 Months All Labor	$2,860	$29
1-Month Maintenance Materials	$157	$2
1-Month Non-Fuel Consumables	$2,236	$22
1-Month Waste Disposal	$9	$0
25% of 1 Month's Fuel Cost at 100% CF	$0	$0
2% of TPC	$2,811	$28
Total	**$8,074**	**$81**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$89	$1
0.5% of TPC (spare parts)	$703	$7
Total	**$792**	**$8**
Other Costs		
Initial Cost for Catalyst and Chemicals	$249	$2
Land	$125	$1
Other Owner's Costs	$21,085	$211
Financing Costs	$3,795	$38
Total Overnight Costs (TOC)	**$174,686**	**$1,747**
TASC Multiplier (IOU, 33 year)	1.093	
Total As-Spent Cost (TASC)	**$190,870**	**$1,909**

Exhibit 6-10. Case 0B-EB initial and annual operating and maintenance costs

Case:	**DAC-0B-EB**	**Sorbent DAC – Electric Boiler (Sensitivity)**			**Cost Base:**	**September 2019**
Plant Size:	**100,000**	**tonnes of CO_2 captured (net)**			**Capacity Factor (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:		1.0
Operating Labor Burden:		30.00	**% of base**	Operator:		3.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		2.0
				Lab Techs, etc.:		2.0
				Total:		**8.0**
Fixed Operating Costs						
					Annual Cost	
					($)	**($/tonne-net)**
Annual Operating Labor:					$3,507,504	$35
Maintenance Labor:					$1,068,306	$11
Administrative & Support Labor:					$1,143,953	$11
Property Taxes and Insurance:					$2,811,333	$28
Total:					**$8,531,096**	**$85**
Variable Operating Costs						
					($)	**($/tonne-net)**
Maintenance Material:					$1,602,460	**$16**
						Consumables
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	-	59	$1.90	$0	$35,836	$0
Makeup and Waste Water Treatment Chemicals (ton):	-	0.18	550	$0	$30,901	$0
Auxiliary Power (kWh):	-	1,199,105	$0.06	$0	$22,321,339	$223
DAC Sorbent (ft³):	62,203	341	$4.00	$248,814	$422,984	$4
Subtotal:				$248,814	$22,811,059	$228
Waste Disposal						
DAC Sorbent (ft³):	0	341	$0.86	$0	$90,941	$1
Subtotal:				$0	$90,941	$1
Variable Operating Costs Total:				**$248,814**	**$24,504,461**	**$245**
Fuel Cost						
Natural Gas (MMBtu):	0	0	$4.42	$0	$0	$0
Total:				**$0**	**$0**	**$0**

6.2.1 Cost Estimate Scaling

The cost estimate for Case 0B-EB was developed using cost estimate results for Case 0-EB (see Appendix B: Case 0-EB – Electric Boiler) as a basis. Case 0-EB considers the same DAC system as Case 0, with the exception of the power and steam generation sub-systems. Case 0-EB utilizes an electric boiler to produce the steam needed for the thermal regeneration of the CO_2 adsorbent. Capital cost estimates for the Case 0-EB DAC system were developed by Black & Veatch and represent an AACE Class 5 estimate, with an uncertainty range of +/-50 percent. For sub-systems that incurred a change in size, flow rate, duty, etc., capital costs were scaled according to the guidance provided in NETL's QGESS: Capital Cost Scaling Methodology: Revision 4 Report. [29] For adjustments to Account 15, the scaling guidance presented in Section 5.3.1 was applied.

6.2.2 Cost of CO_2 Capture Results

Using the methodology presented in Section 3.6, Exhibit 6-11 presents the results for the COC for Case 0B-EB.

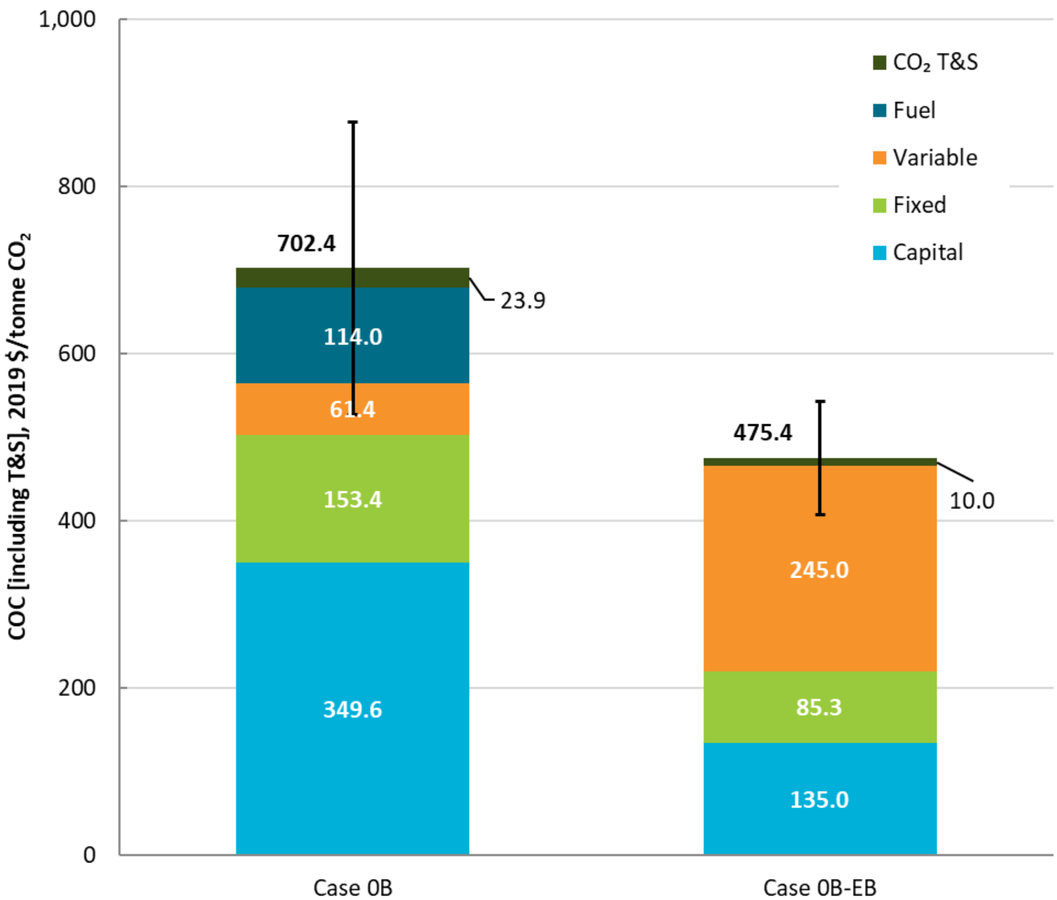
Exhibit 6-11. Case 0B-EB COC

Component	COC DAC_{net}, $/tonne
Capital	135.0
Fixed	85.3
Variable	245.0
Fuel	0.0
Total (Excluding T&S)	465.4
CO_2 T&S	10.0
Total (Including T&S)	475.4

For the COC DAC_{net} result of $475/tonne CO_2 ($431/ton CO_2) (including T&S), a total CO_2 flow of 100,000 tonnes/yr (110,230 tons CO_2/yr) is used. In Case 0B-EB, auxiliary load requirements are fulfilled by renewable electricity; for simplicity, it is assumed that the renewable electricity source produces power with no process-related CO_2 emissions. Therefore, in Case 0B-EB, the net capture rate is equivalent to the gross capture rate.

Exhibit 6-12 presents the COC results graphically and includes error bars relating to the uncertainty in the capital cost estimate. The COC result of Case 0B is also included for comparison. As highlighted previously, the capital estimates represent AACE Class 5 estimates, with an uncertainty range of +/-50 percent. The COC ranges presented are not reflective of other changes, such as variation in fuel price, labor price, CF, or other factors.

Exhibit 6-12. Case 0B and Case 0B-EB COC plot and uncertainty ranges



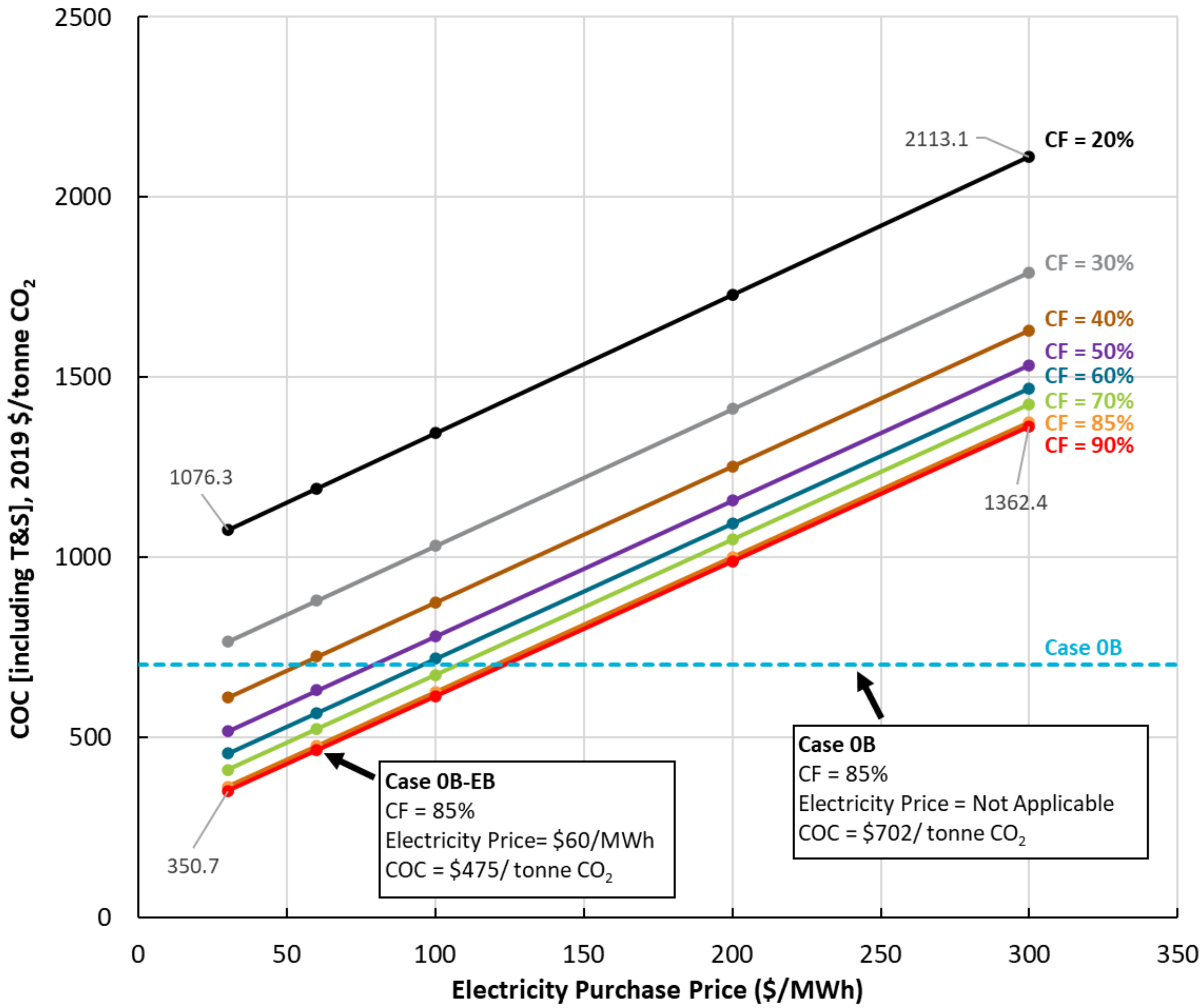
Note: Case 0B-EB assumes that the auxiliary load is satisfied by purchased electricity at a price of $60/MWh. Additionally, for purposes of sizing the plant, it assumes that the purchased electricity has no associated process CO_2 emissions

6.2.3 Sensitivity Analysis

In Case 0B-EB, it is assumed that all electricity requirements are fulfilled by renewable sources with no associated CO_2 emissions. Because the selling price and CF of renewable electricity may vary depending on generation technology type, region, inclusion of energy storage, and other factors, a sensitivity analysis was conducted over a range of electricity purchase prices and CFs.

Exhibit 6-13 shows the net COC sensitivity to electricity purchase price for several different assumed CFs. Electricity prices ranging $30–300/MWh and CFs ranging 20–90 percent were considered. Over this range of electricity prices and CFs, the COC ranges $351–2,113/tonnes CO_2. At CFs of 30 percent and lower, the COC range is above the COC result for Case 0B even at the lowest electricity price assumed ($30/MWh). At a CF of 40 percent, the price of purchased electricity must be less than $54/MWh in order to achieve a COC lower than Case 0B. At 90 percent CF, the price of purchased electricity must be less than $124/MWh in order to achieve a COC lower than Case 0B.

Exhibit 6-13. Case 0B-EB COC sensitivity to electricity purchase price and CF



Note: The system energy requirements (both electric and thermal) in Case 0B-EB and Case 0B-EB sensitivities are satisfied by electricity purchase (thermal requirements satisfied by an electric boiler). The Case 0B COC is presented for comparison with Case 0B-EB and Case 0B-EB sensitivity results. The system energy requirements (both electric and thermal) in Case 0B are provided by an NGCC with 90% capture. To account for process CO_2 emissions, the gross DAC capacity in Case 0B is upsized by 14% compared to the gross capture capacity of Case 0B-EB.

When considering the potential variability of renewable sources without sufficient energy storage to smooth out disruptions in supply, and the potential increase in LCOE for renewables sources paired with sufficient energy storage, the base result presented in Section 6.2.2 for Case 0B-EB is viewed as overly optimistic. While low and negative LCOEs have been highlighted in the literature as a result of excess renewable generation during periods of low demand and high renewable availability, [31] it is unrealistic to assume that these low LCOE values would be available to the DAC plant for large portions of a single day. Therefore, from the perspective of impact of CF and LCOE on the COC result for the Case 0B-EB configuration considered, there is little opportunity to reduce the COC beyond the Case 0B-EB result shown by only considering these two parameters. Other parameters, such as assumed system pressure drop, will be more impactful. If system pressure drop were able to be reduced, the electrical auxiliary load of Case

0B-EB would reduce, and all the lines in Exhibit 6-13 would shift down. However, applying this same system pressure drop reduction to Case 0B would also shift the Case 0B COC result down. Thus, it is assumed that the relative comparison of Case 0B and Case 0B-EB COC results would remain largely the same, but that the absolute results compared with other sources of CO_2 may become more favorable for these DAC configurations.

7 CONCLUSIONS

In recent years, there has been a significant increase in research focused on DAC, but to date, the technology is immature. There have been developers that have advanced to small pilot-scale testing of their processes and published projected performance and cost estimates, [1] [2] but these technologies require further R&D, which is ongoing. [5] Other developers have stated publicly that they have constructed and are currently operating DAC plants, but the level of detail publicly available for these plants limits assessment and understanding. [6]

The objective of this study is to develop an independent assessment of the performance and cost of a generic sorbent-based DAC system. Several potential process configurations were considered. As was detailed in the process development section, if the DAC plant presented in this study was to purchase power exclusively from the grid, the auxiliary load of the DAC-specific process equipment (e.g., air fans and DAC-only CO_2 compressor) would require grid electricity with an average grid emissions profile below 332 kg CO_2/MWh (732 lb CO_2/MWh) for a monolith sorbent configuration, to result in a true negative-emissions technology. This value is approximately one third lower than the current U.S. grid mix emissions profile. [20] To meet the target plant size considered in this study, the emissions profile of the electricity must be well below this breakeven point to minimize the gross size of the DAC plant, and the resulting COC from the DAC plant. This simple comparison does not take into account a full life cycle emissions accounting of all the potential sources of emissions, but rather, is only focused on the potential power generation point source emissions. This result suggests that for DAC processes to be configured to purchase electricity from the grid to satisfy all the plant electrical auxiliary load, the system would need to be heavily supplied by low-carbon renewable sources or have a very low electrical auxiliary load, well below that represented for Case 0B.

The sorbent considered represents the approximate average of performance reported in the literature. The system configuration considered represents what was judged to be the most reasonable configuration if these systems were to be deployed in the near term. Specifically, Case 0B considers a CT, HRSG, and ST that produce electricity to support plant auxiliary load and steam for all plant thermal requirements. The HRSG flue gas CO_2 is captured at a rate of 90 percent using Shell's Cansolv system, with a dedicated CO_2 compressor to compress only the CO_2 product from the Cansolv system. Air fans pressurize and deliver inlet air to the DAC adsorbers that remove CO_2 from the inlet air at a 60 percent capture rate, and regenerate with indirect steam used to produce a CO_2 product stream that is compressed with a dedicated DAC CO_2 compressor. The system is sized for a net air removal of 100,000 tonnes CO_2/yr (110,230 tons CO_2/yr), based on the 2018 minimum 45Q tax credit threshold for DAC systems. [4]

Case 0B results in a COC_{net} of \$702/tonne (\$637/ton). When considering the gross flow of CO_2 from only the DAC adsorbers (COC DAC_{gross}), the COC reduces to \$617/tonne (\$560/ton). When considering the total flow of CO_2 from the plant, including from the DAC adsorbers and Shell's Cansolv system, the COC reduces further to \$294/tonne CO_2 (\$267/ton CO_2). The high COC is reflective of the need to capture over 240,000 tonnes CO_2/yr (260,000 tons CO_2/yr) to achieve a net removal of 100,000 tonnes/yr (110,230 tons CO_2/yr) from the atmosphere. Note that many cost and performance assumptions Case 0B and Case 0B-EB are fairly optimistic and could result in a best-case COC.

In order to assess a possible renewables-based DAC system, an additional case was evaluated that utilizes an electric boiler for steam requirements. This case, Case 0B-EB, considers the same DAC system as Case 0B, with the exception of the power and steam generation sub-systems. It is assumed that the electricity required to satisfy the auxiliary load in Case 0B-EB produces no process CO_2 emissions and is purchased at a sale price of $60/MWh. For Case 0B-EB, the capital and operating cost estimates presented result in a net COC of $475/tonne CO_2 ($431/ton CO_2) (including T&S). This result is based on a total CO_2 flow of 100,000 tonnes/yr (110,230 tons CO_2/yr) of net CO_2 removed from the atmosphere.

In order to gauge the impact of different renewable electricity sources for Case 0B-EB, sensitivities were conducted on CF and the sale price of purchased electricity. At CFs of 30 percent and lower, the COC range for Case 0B-EB is above the COC result for Case 0B even at the lowest electricity price assumed ($30/MWh). At a CF of 40 percent, the price of purchased electricity must be less than $54/MWh in order to achieve a COC lower than Case 0B. At 90 percent CF, the price of purchased electricity must be less than $124/MWh in order to achieve a COC lower than Case 0B.

There are several process- and material-related unknowns associated with this technology and therefore, sensitivity analysis was performed on several critical parameters using the Case 0B plant configuration. Changes in assumptions and minor changes in process configuration demonstrated the ability to reduce the COC; however, for a 100,000 tonne/year capture system, none of the sensitivity studies independently demonstrated a COC_{net} below $500/tonne ($455/ton). The effects of the sensitivity cases would likely be additive, however, and a cumulative case would be expected to result in a COC_{net} below $500/tonne CO_2. Scaling to higher capture rates can reduce the COC_{net} to below $500/tonne; COC_{net} drops to $430/tonne CO_2 when the system scaled to capture 1,000,000 tonne/yr.

Given the lack of literature data and references for these systems, several assumptions were made, and these assumptions should be further refined to enhance the results presented. Section 8 provides several suggestions, but not a complete list, for future work that would aid in refining the generic DAC sorbent system results presented.

8 Future Work

8.1 Operational Considerations of the Plant Equipment

8.1.1 Air Fans

As described in Section 5.1 , the Case 0B operating profile assumes that adsorber vessels will go through a 3-hour adsorption phase, followed by an 18-minute desorption phase. During the 18-minute desorption phase, inlet air flow is not required from the air fans. In the process configuration, one air fan is included for two adsorber vessels. In Case 0B, the operating profile assumes that the air fans would continue to operate but would be throttled for the 18-minute desorption period. This represents more than a 2-hour window of inefficient operation every day. Alternate configurations for this approach were not considered. Future work could look at the tradeoff between the increased maintenance cost and potential decreased reliability to shut down the air fans for 10 hours every 100 hours, versus the additional cost to include ducting such that the air fans would run 100 percent of the time but have the ability to switch between sending air to one block of vessels versus another.

8.1.2 CO_2 Compressor

The considered configuration assumes that a single reciprocating CO_2 compressor would compress the CO_2 product sourced from all vessels. When the adsorber vessels switch from adsorption phase to regeneration phase, inlet air will be shut off, steam will begin to flow through the inner-adsorber heating coils, and this heat will distribute through the bed providing the driving force to desorb CO_2 from the surface of the sorbent. The adsorber vessel will be open to the CO_2 compressor, which will provide suction to pull the CO_2 through the product piping and to the compressor inlet. The desorption cycle assumed is 18 minutes, and in practice, it is expected that the flow of CO_2 will be variable based on the rate of heating of the sorbent bed in the vessel, and the resulting rate of desorption of CO_2 from the sorbent. There was no consideration given to how this variable flow may impact the CO_2 compressor. Several options could be investigated as part of future work, including implementing a surge tank to smooth out variable flow rate to the CO_2 compressor; use of recirculation within the CO_2 compressor envelope, which could provide a steady inlet flow to the compressor but would likely increase the auxiliary load of the compressor and require a larger CT to account for the increased electrical auxiliary load; operational considerations focusing on the timing of desorption cycles that may allow for more consistent flow rates to the CO_2 compressor; and others as appropriate.

8.2 Alternate Configuration Considerations

8.2.1 Combustion Turbine

Case B31B from NETL's BBR4 is used as a reference starting point for performance modeling and cost estimation. In pursuing this path, the F-class CTs used in Case B31B were treated as "rubber turbines" for this study; in other words, the output was scaled down to match that needed by Case 0's electrical auxiliary load demand and steam demand. In practice, CT manufacturers likely will not custom-size a turbine output for a given application, and projects will need to select off-the-shelf technology. Given the size of Case 0B, smaller aeroderivative CTs are a more likely technology choice. Future work could investigate the use of:

- Aeroderivative CTs: aeroderivative CTs will have different performance characteristics and capital costs that may shift the results presented. In addition, the aeroderivative CT exhaust temperatures may be different, which will impact the performance of the HRSG, and could shift the results presented.
- A full-scale NGCC plant with excess power sales: this option will benefit from economies of scale and lead to reduced system cost.

Moreover, since Case B31B from NETL's BBR4 is used as the reference starting point for performance modeling and cost estimation, only 90 percent CO_2 capture from the NGCC flue gas is considered. Future work can investigate implementing CO_2 capture systems with higher capture rates. Higher capture rates reduce the total amount of CO_2 that would need to be captured by the DAC system to meet the net capture rate goal. Higher capture rates up to at least 97 percent are expected to increase process efficiency and reduce COC.

8.2.2 Adsorber Vessel Size/Optimization

As highlighted several times throughout this study, there are limited data available in the literature detailing process configurations and parameters for DAC sorbent systems. Therefore, certain parameters such as pressure drop have been determined based on assumptions for air velocity, sorbent void fraction, and other sorbent parameters, as well as assumed adsorber vessel sizing parameters such as vessel diameter and bed depth. Working backward from what was judged to be a reasonable pressure drop, a vessel diameter was selected that allowed for the target pressure drop while also providing what was judged to be a reasonable number of vessels required to produce the target CO_2 flow. Within this context, there are many different combinations of parameter solutions that would result in the target pressure drop. Exhibit 8-1 shows some of the many potential vessel-diameter options versus number-of-vessels-required options that could satisfy the pressure drop and product flow requirements of Case 0B.

Exhibit 8-1. Vessel size versus number of vessels required, Case 0B

Vessel Diameter, ft	Minimum Number of Vessels Required
60	20
50	30
40	44
30	70
20	150

Future work could look to further optimize the multitude of parameters that factor into system configuration, vessel sizing, and number of vessels required. Future work should also investigate configurations that seek to minimize pressure drop both through plant layout and alternate sorbent configurations.

Vessel diameter, bed depth, air velocity, and adsorption cycle time will all impact the adsorption capacity achieved by the sorbent in the bed. Future work examining optimized system configurations could also look to determine the optimum adsorption/desorption cycle time, and the optimum or most realistic sorbent loading (sorbent adsorption capacity and selectivity).

Future work could also examine the potential use of non-ferrous components (e.g., fiberglass reinforced plastic pipe) for vessel construction to expedite construction, and more closely relate the measured adsorption isotherms of materials presented in the literature with the vessel assumptions (i.e., bed depth, breakthrough time). Detailed design of the heat transfer mechanism within the vessel was also not pursued as part of this work. Future work could look to refine the vessel internals, and more directly relate the rate of sorbent bed heating with the expected performance of the convective heat transfer configuration considered.

8.2.3 Plant Layout/Air Dispersion Considerations

Considerations for how close the adsorber vessels can be spaced, given concerns around entrained sorbent particles potentially being present in the adsorber vessel air outlet, and changes to the local air composition around the vessels where air mixing is occurring, were not explicitly considered in this study. Changes to plant layout would likely have a small impact on the results. Increases in overall plant size would impact the Owner's Cost Land Purchase total, which is relatively small. Increasing the space between adsorber vessels would also increase the cost of air handling ducting and desorption process gas handling systems. Future work could examine this consideration in an effort to refine the plant configuration concept.

8.3 Financial Parameter Considerations

As described in Section 3.6, the financial parameter assumptions used to calculate the COC were sourced from NETL's BBR4, and represent the financial assumptions used to calculate the COE for NGCC power plants. Future work could look to develop DAC-specific financial assumptions: a reference case set of assumptions for today's markets, possibly reflective of the chemical industry, and incorporating high-risk aspects given the lack of maturity of the DAC technology; a future set of assumptions building in the de-risking of DAC as the technology deploys and matures; sensitivity assumptions building in options for special financial considerations or programs (e.g., loan guarantee programs); and others as determined to be appropriate. This future work would improve upon the FCR sensitivity examined in this study, as the scenarios would be more closely tied to real-world financial scenarios.

9 REFERENCES

[1] "Climeworks Starts Paid Carbon Dioxide Removal," CleanTechnica, 17 June 2019. [Online]. Available: https://cleantechnica.com/2019/06/17/climeworks-starts-paid-carbon-dioxide-removal/. [Accessed 27 September 2019].

[2] D. W. Keith, G. Holmes, D. St. Angelo and K. Heidel, "A Process for Capturing CO2 from the Atmosphere," *Joule,* pp. 1573-1594, August 15, 2018.

[3] DOE Office of Fossil Energy and Carbon Management, "Carbon Negative Shot," [Online]. Available: https://www.energy.gov/fecm/carbon-negative-shot. [Accessed 2022].

[4] "26 USC 45Q: Credit for Carbon Oxide Sequestration," [Online]. Available: https://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim). [Accessed 26 September 2019].

[5] NETL, "Proceedings - Carbon Management and Oil and Gas Research Project Review Meeting - Carbon Dioxide Removal Research," DOE, 2021. [Online]. Available: https://netl.doe.gov/21CMOG_CDRR_proceedings. [Accessed 2022].

[6] Climeworks, "Climeworks Facts & Figures," [Online]. Available: https://climeworks.com/. [Accessed November 2021].

[7] The National Academy of Sciences, Engineering, and Medicine, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," Washington, DC, 2016.

[8] E. S. Sanz-Perez, C. R. Murdock, S. A. Didas and C. W. Jones, "Direct Capture of CO2 from Ambient Air," *Chemical Reviews,* vol. 116, pp. 11840-11876, 2016.

[9] Q. Yu and D. Brilman, "Design strategy for CO2 adsorption from ambient air using a supported amine based sorbent in a fixed bed reactor," *Energy Procedia,* vol. 114, pp. 6102-6114, 2017.

[10] W. Zhang, H. Liu, C. Sun, T. C. Drage and C. E. Snape, "Capturing CO2 from ambient air using polyethyleneimine-silica adsorbent in fluidized beds," *Chemical Engineering Science,* vol. 116, pp. 306-316, 2014.

[11] M. Fasihi, O. Efimova and C. Breyer, "Techno-economic assessment of CO2 direct air capture plants," *Journal of Cleaner Production,* vol. 224, pp. 957-980, 2019.

[12] A. R. Kulkarni and D. S. Sholl, "Analysis of Equilibrium-Based TSA Processes for Direct Capture of CO2 from Air," *I&EC Research,* vol. 51, pp. 8631-8645, 2012.

[13] A. Sinha, L. A. Darunte, C. W. Jones, M. J. Realff and Y. Kawajiri, "Systems Design and Economic Analysis of Direct Air Capture of CO2 through Temperature Vacuum Swing Adsorption Using MIL-101 (Cr)-PEI-800 and mmen-Mg2(dobpdc) MOF Adsorbents," *I&EC Research,* vol. 56, pp. 750-764, 2017.

[14] C. J. E. Bajamundi, J. Koponen, V. Ruuskanen, J. Elfving, A. Kosonen, J. Kauppinen and J. Ahola, "Capturing CO2 from air: Technical performance and process control improvement," *Journal of CO2 Utilization,* vol. 30, pp. 232-239, 2019.

[15] American Physical Society, "Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs," June 2011.

[16] NETL, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 4," DOE, Pittsburgh, PA, 2019.

[17] NETL, "Quality Guidelines for Energy System Studies: Specification for Selected Feedstocks," DOE, Pittsburgh, PA, 2019.

[18] Gas Research Institute, Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States, Springfield: U.S. Department of Commerce, 1992.

[19] NETL, "Quality Guidelines for Energy System Studies: Fuel Prices for Selected Feedstocks in NETL Studies," DOE, Pittsburgh, PA, 2019.

[20] NETL, "NETL Grid Mix Explorer," DOE, Pittsburgh, PA, 2016.

[21] NETL, "Quality Guidelines for Energy System Studies: Carbon Dioxide Transport and Storage Costs in NETL Studies," DOE, Pittsburgh, PA, 2019.

[22] NETL, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessment of Power Plant Performance," DOE, Pittsburgh, PA, 2019.

[23] M. Sakwa-Novak, C.-J. Yoo, S. Tan, F. Rashidi and C. Jones, "Poly(ethylenimine)-Functionalized Monolithic Alumina Honeycomb Adsorbents for CO2 Capture from Air," *ChemSusChem,* 2016.

[24] A. R. Sujan, S. H. Pang, G. Zhu, C. Jones and R. Lively, "Direct CO2 Capture from Air using Poly(ethylenimine)-Loaded Polymer/Silica Fiber Sorbents," *ACS Sustainable Chemistry & Engineering,* 2019.

[25] L. Darunte, Y. Terada, C. Murdock, K. Walton, D. Sholl and C. Jones, "Monolith-Supported Amine-Functionalized Mg2(dobpdc) Adsorbents for CO2 Capture," *Applied Materials & Interfaces,* 2017.

[26] F. Rezaei and P. Webley, "Optimum structured adsorbents for gas separation processes," *Chemical Engineering Science,* 2009.

[27] GE Power, "7F Power Plants," November 2017. [Online]. Available: https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/gas%20turbines/Fact%20Sheet/2018-prod-specs/7f-power-plants.pdf. [Accessed 10 May 2018].

[28] L. B. Davis and S. Black, "Dry Low NOx Combustions Systems for GE Heavy-Duty Gas Turbines," GE Power Systems, October 2000.

[29] NETL, "Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology: Revision 4 Report," DOE, Pittsburgh, PA, 2019.

[30] NETL, "Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants," DOE, Pittsburgh, PA, October 2017.

[31] E. Mundahl, "California Renewables and the Mystery of Negative Power Prices," 9 August 2018. [Online]. Available: https://www.insidesources.com/california-renewables-and-the-mystery-of-negative-power-prices/. [Accessed 16 June 2020].

APPENDIX A: REFERENCE CASE 0

A.1 FINAL REFERENCE CASE 0 PROCESS CONFIGURATION

The final process configuration considered in development of Case 0 includes the use of a natural gas combined cycle (NGCC) plant to provide the electrical auxiliary load and steam requirements of the direct air capture (DAC) system, and the CO_2 present in the flue gas from the NGCC plant is captured at a rate of 90 percent. Inlet air is passed through fans that provide the motive force to deliver the air to the DAC adsorber vessels, and overcome the pressure drop of the duct distribution system as well as the pressure drop of the sorbent packed bed. During the adsorption phase, the air exits the top of the vessels. During desorption, steam is provided to the vessels via internal heating coils and provides the driving force to desorb CO_2 from the sorbent.

The NGCC plant is modeled after the reference Case B31B presented in the National Energy Technology Laboratory's (NETL) Bituminous Baseline Revision 4 (BBR4). [16] Sub-system descriptions for the NGCC plant can be found in the reference report and are not replicated here.

There were two notable changes made from the reference Case B31B. Given the size, and electrical demand of the DAC system, only a single combustion turbine (CT) is considered. In addition, in the referenced study, a single CT provides a gross electrical output of 239 MW, which is well beyond what is required for the DAC system. The CT in the reference study was scaled down (i.e., treated as a "rubber turbine") to match the electrical requirements of the DAC system. In practice, smaller-scale CTs, such as aeroderivative CTs, would be a more technically feasible option for this type of plant. The second notable change is that the reference Case B31B considered a triple pressure heat recovery steam generator (HRSG), supplying a triple pressure steam turbine (ST) bottoming cycle. Given the steam requirements of the DAC system, the HRSG was adjusted to produce saturated steam at a single pressure (0.51 MPa [73.5 psia]). Any steam requirements of the system that exceeded the temperature of this steam (e.g., Shell's Cansolv requirements for solvent purification, or triethylene glycol [TEG] dryer requirements for CO_2 compression) were assumed to be met by superheating the low-pressure steam to the required temperature. Any excess steam generated by the HRSG that was not needed by Shell's Cansolv unit or DAC process was sent to a single-stage low-pressure steam cycle. The combined electrical output of the ST and CT was adjusted such that it met the total plant auxiliary loads exactly, with no excess available for sale to the grid, or deficit requiring purchase from the grid.

The DAC plant layout is provided in Exhibit A-1. The plant layout was chosen due to its ability to optimize efficiency and the overall footprint of the facility. This is accomplished by co-locating components to the greatest extent practical. Examples include placing the NGCC components (e.g., CT building, ST building, and cooling towers) in as close proximity as would be practical. This arrangement minimizes the amount of piping material needed for the various steam, feedwater, and cooling water systems. Another example is the placement of the material handling silos directly over the road for expedited delivery of the new sorbent and haul-off of the spent sorbent. This arrangement mirrors arrangements for facilities utilizing similar type of equipment for ash loading or consumable (e.g., powder-activated carbon) off-loading to the plant material handling system(s).

The separate new sorbent and spent sorbent silos are mirrored across the north/south split of the facility and placed as close to the vessel array as possible to reduce material costs and pneumatic conveying line losses. These pneumatic conveying lines would only be utilized during scheduled shutdowns for the sorbent changeouts.

The array of adsorber vessels is set up in a square pattern to minimize plant area while also providing suitable space for access and maintenance in and around the vessels. An estimated wall-to-wall separation of 3 m (10 feet) is reflected in the plant layout shown. To reduce the total linear feet of air duct needed to convey the ambient air through the adsorber vessels, the centrifugal air fans were divided into 12 groups of 5 with each group of 5 fans intended to serve 1 north/south 'column' of 10 vessels. Locating the fans as close as possible to their assigned vessels reduces duct pressure loss and auxiliary power of the centrifugal fans. This east/west corridor through the vessels is also intended to provide a simplified routing corridor for the DAC process off-gas (i.e., CO_2) piping as it is transported to the DAC processing area.

The facility layout was further optimized through the location of the various sub-process buildings. Mirroring other chemical process facilities, the administration building (including the control room) is co-located near the NGCC equipment. The warehouse, machine shop, and ancillary storage building is located on the west side of the vessel array to safely demarcate maintenance activities (i.e., welding, volatile material storage, maintenance vehicle storage, etc.) separate from the critical facility equipment (CT, ST, gas compressors, etc.).

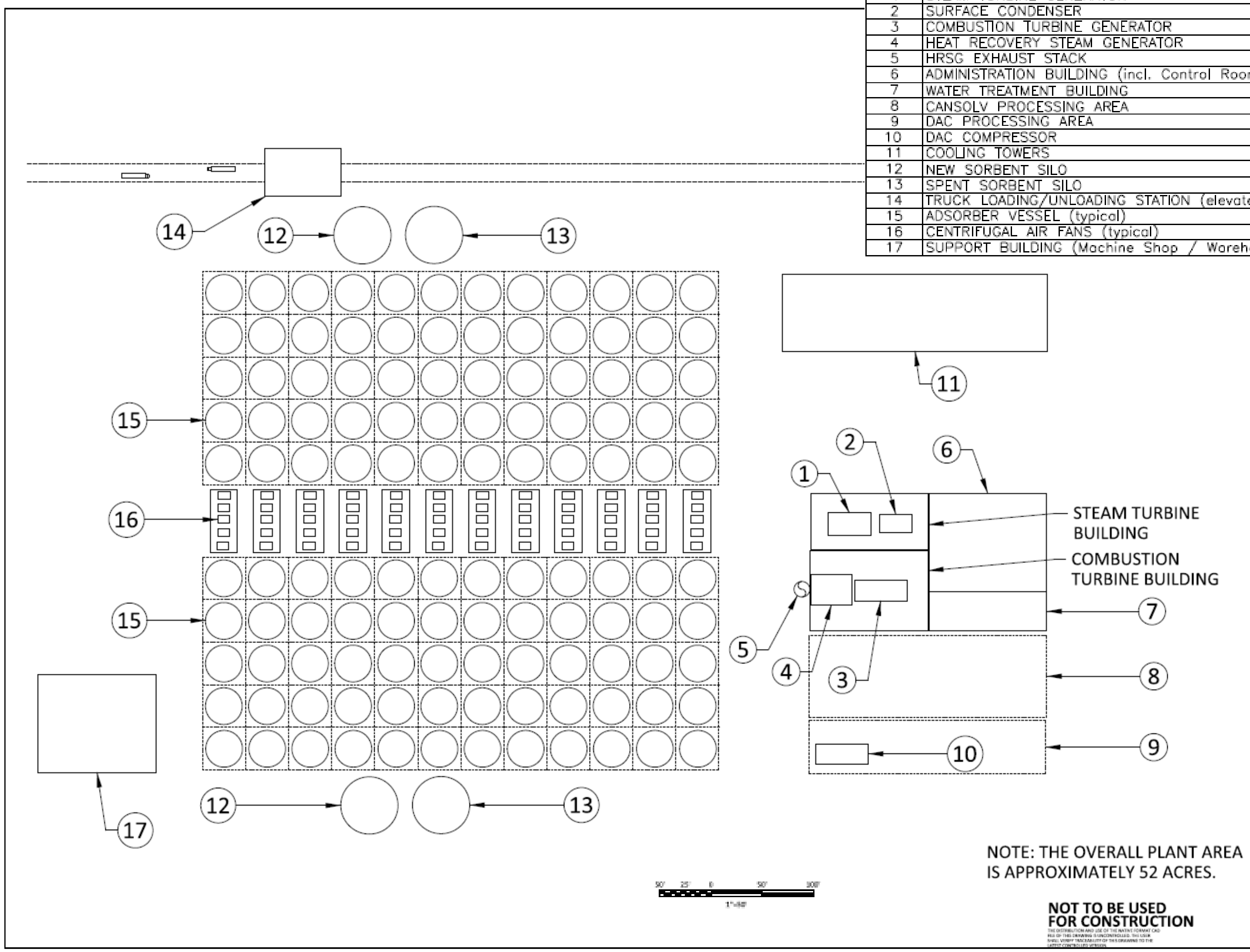
The following sub-sections provide additional description of sub-systems specific to the DAC portion of the process referred to in Exhibit A-1.

A.1.1 Inlet Air Handling System

The inlet air handling sub-system controls the movement of air via the use of centrifugal fans, ducting, and guillotine dampers. The system comprises 60 centrifugal fans (with 1 additional spare fan for a total of 61) that serve the 120 adsorber vessels in Case 0. In Exhibit A-1, the air handling fans are arranged in 12 groups of five; each group of five fans serves a north/south 'column' of 10 adsorber reactor vessels. The spare fan is provided for 'N+1' redundancy. The ambient air enters through inlet boxes of the centrifugal fans, exits the fan to be discharged through the air duct system and from the air duct system is routed to the bottom of the adsorber vessel(s) where it is then routed vertically upward to flow across the solid-sorbent bed. Once past the bed, the ambient air exits the vessel through a short, weather-protected, circular 90-degree transition piece that safely exhausts the air back to ambient at a horizontal orientation. The fans will be operated at constant speed and flow independent of vessel operations; during the relatively short desorption process, the output of the air fans can be reduced using the inlet throttling mechanism (e.g., variable inlet vanes). The air duct will be constructed of standard carbon steel with interior and exterior stiffeners for additional support. Throughout the handling process, pressure losses will be mitigated by incorporating flow straightening devices within the duct to maintain efficiency.

Exhibit A-1. Site layout drawing for Case 0

ITEM NO.	EQUIPMENT IDENTIFICATION LIST
1	STEAM TURBINE GENERATOR
2	SURFACE CONDENSER
3	COMBUSTION TURBINE GENERATOR
4	HEAT RECOVERY STEAM GENERATOR
5	HRSG EXHAUST STACK
6	ADMINISTRATION BUILDING (incl. Control Room)
7	WATER TREATMENT BUILDING
8	CANSOLV PROCESSING AREA
9	DAC PROCESSING AREA
10	DAC COMPRESSOR
11	COOLING TOWERS
12	NEW SORBENT SILO
13	SPENT SORBENT SILO
14	TRUCK LOADING/UNLOADING STATION (elevated)
15	ADSORBER VESSEL (typical)
16	CENTRIFUGAL AIR FANS (typical)
17	SUPPORT BUILDING (Machine Shop / Warehouse)



A.1.2 Vessel Operations

The reactor vessel is an 18.3-meter (60-foot) diameter cylindrical container constructed from welded carbon steel plates. The vessels will be approximately 9.1 m (30 feet) tall and elevated to allow enough room for air duct and pipe routing underneath the vessel. Each vessel will also be equipped with both internal and external stiffeners. Inside the bottom of each vessel will be the fixed bed of sorbent that will be interfaced with an indirect heating element, which is heated by the steam supplied from the HRSG. Large guillotine dampers will be fitted on both inlets and outlets of each vessel to allow the vessel to provide high integrity isolation during the capture process. The vessel array characterized in Case 0 consists of 120 vessels; it has been assumed that no redundant (i.e., normally out of service) vessels have been included in the vessel array.

The vessel will begin by receiving new sorbent from the material handling system and loading it into the bed portion of the vessel, to be filled in around the heating element. The process of adsorption starts by circulating air into the open vessel from ambient. The sorbent will begin to bond and remove the CO_2 from the air as it passes through the vessel; air that passes through the bed will be exhausted out the top of the vessel. Once adsorption is complete, both dampers (inlet/outlet) will close, isolating the vessel. Due to the less-than-ideal Case 0 packed bed configuration, the adsorption process lasts for approximately 90 hours.

Desorption immediately begins, and the steam will be routed through the fixed bed heating coils thereby providing the necessary regeneration energy to the sorbent. The heat will cause the sorbent to release the captured CO_2. During the heating, the CO_2 compressor will draw suction from the applicable vessels into the DAC process product gas handling system. Once desorption is complete, the sorbent is ready for the adsorption process to begin again, starting with the opening of inlet/outlet guillotine dampers and resuming the flow of ambient air. Due to the less-than-ideal Case 0 packed bed configuration, the desorption process lasts for approximately 10 hours.

A.1.3 Sorbent Material Handling System

The material handling sub-system controls the movement and storage of the new and spent solid sorbent throughout the DAC facility. The handling system comprises the truck loading/offloading components, the storage silos, and the pneumatic conveying piping. Sorbent will only be loaded/unloaded during the semi-annual scheduled plant outages. During this time, sorbent is transferred from the interim silos to each individual vessel for utilization in the capture process. While this is underway, the spent sorbent is traveling out of the vessel in a separate transport pathway to be delivered to the spent sorbent silo near the truck loading area. From the truck loading area, it is transported offsite and disposed. The sorbent handling system will be customized to the specific attributes of the selected DAC sorbent. Solid handling system issues were not considered beyond sorbent lifetime sensitivity. It should be noted that this system is not required for the monolith cases. The capital cost of this system accounts for <2 percent of the capital cost of the DAC systems; therefore, including this cost for the monolith cases does not impact costs.

A.1.4 DAC Process Off-Gas Handling System

The safe control and handling of DAC adsorber vessel off-gas (i.e., CO_2) is managed by the DAC process off-gas handling system. This system comprises the off-gas isolation valves (one per vessel), the carbon steel piping connecting the vessels to the DAC processing areas, the DAC reciprocating compressor (one for the entire facility), a glycol-based closed-loop heat exchanger, and the compressor intercoolers. CO_2, along with other off-gas constituents will be produced from the sorbent as the regeneration energy is supplied during the desorption process. The off-gas will be routed via carbon steel piping to the DAC processing area shown as item 9 in Exhibit A-1. The gas will be cooled to remove moisture and then compressed to pipeline specifications for transmission.

A.2 Reference Case 0 – Performance and Cost Estimates

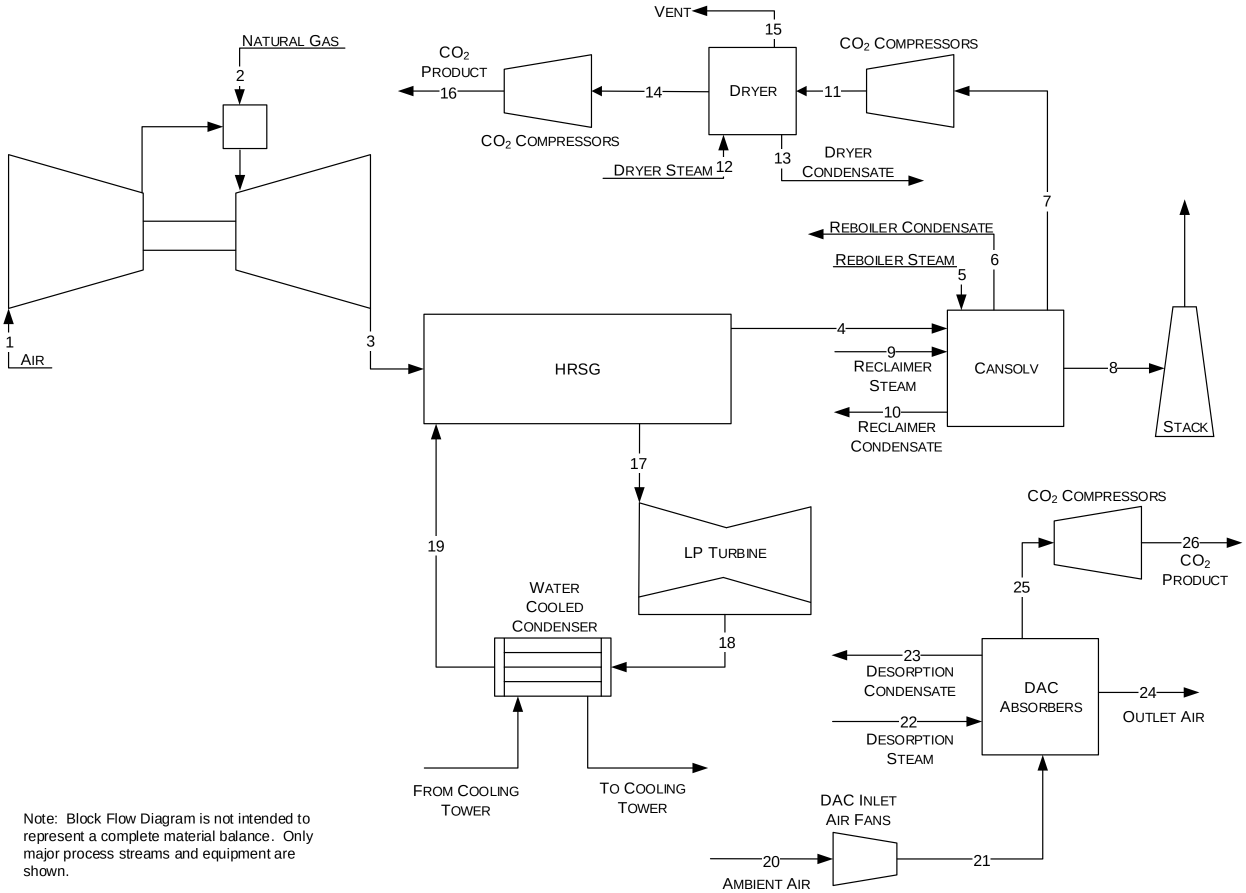
This section describes the DAC system. The system description follows the block flow diagram (BFD) in Exhibit A-2 and stream numbers reference the same exhibit. Exhibit A-3 provides process data for the numbered streams in the BFD. The DAC portion of the process considers 120 adsorber vessels and 60 air fans, but the flow rates in the stream table represent the total system.

A.2.1 Case 0 – Process Description and Performance Results

The development of the DAC system configuration and final determination of modeling assumptions were presented previously in Sections 3 and 4.

Case 0 captures a net 100,000 tonnes CO_2/yr (110,230 tons/yr) from the atmosphere. The plant is electricity neutral; it does not have excess electricity to sell on the grid, nor does it require purchased power to satisfy plant auxiliary loads.

Exhibit A-2. Case 0 BFD, sorbent-based DAC system



Ambient air (stream 1) is supplied to an inlet filter and compressed before being combined with natural gas (stream 2) in the dry low-NOx burners (LNBs), which is operated to control the rotor inlet temperature at 1,423°C (2,594°F). The flue gas exits the turbine at 624°C (1,156°F) (stream 3) and passes into the HRSG. The single-pressure HRSG generates 0.51 MPa (73.5 psia) steam, the majority of which is directly used in Shell's Cansolv unit (stream 5) for solvent regeneration, and in the DAC adsorbers (stream 22) for sorbent regeneration. A small portion of the steam is superheated for use in the capture solvent reclaimer (stream 9) and CO_2 TEG dryer (stream 12). The balance of the steam generated by the HRSG is sent to a small steam bottoming cycle (stream 17). Flue gas exits the HRSG at 167°C (332°F) (stream 4) and passes to Shell's Cansolv carbon capture facility, where 90 percent of the flue gas CO_2 is removed, (stream 7), dried, and compressed to 15.2 MPa (2,200 psig) (stream 16). The purified flue gas leaves through the stack (stream 8). Ambient air (stream 20) is sent through fans and a duct system to distribute air to the 120 DAC adsorber vessels (stream 21). During steady-state operations, 108 of the 120 vessels will be operating in adsorption mode (90-hour cycle) and receiving air from the fans. The other 12 adsorption vessels will be in desorption mode (10-hour cycle) and utilize steam from the HRSG (stream 22) to drive CO_2 from the sorbent. The product CO_2 is pulled from the adsorber vessels to the CO_2 compressor (stream 25), where it is compressed to 15.2 MPa (2,200 psig) (stream 26).

Exhibit A-3. Case 0 stream table, sorbent-based DAC system

	1	2	3	4	5	6	7	8	9	10	11	12	13
V-L Mole Fraction													
Ar	0.0092	0.0000	0.0088	0.0088	0.0000	0.0000	0.0000	0.0097	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.9310	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0004	0.0100	0.0409	0.0409	0.0000	0.0000	0.9865	0.0045	0.0000	0.0000	0.9961	0.0000	0.0000
H_2O	0.0101	0.0000	0.0877	0.0877	1.0000	1.0000	0.0135	0.0358	1.0000	1.0000	0.0039	1.0000	1.0000
N_2	0.7724	0.0160	0.7421	0.7421	0.0000	0.0000	0.0000	0.8174	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.2079	0.0000	0.1204	0.1204	0.0000	0.0000	0.0000	0.1326	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	21,665	878	22,569	22,569	2,623	2,623	842	20,490	20	20	834	1	1
V-L Flowrate (kg/hr)	625,190	15,209	640,398	640,398	47,259	47,259	36,777	581,352	362	362	36,631	21	21
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	27	625	167	153	152	30	30	216	152	29	204	152
Pressure (MPa, abs)	0.10	2.96	0.11	0.10	0.51	0.49	0.20	0.10	0.50	0.49	3.04	0.50	0.49
Steam Table Enthalpy (kJ/kg)[A]	30.65	22.04	833.27	315.61	2,773.62	635.56	38.37	87.89	2,897.38	635.56	-4.49	2,875.21	635.56
Aspen Plus Enthalpy (kJ/kg)[B]	-100.89	-4,487.18	-647.50	-1,165.16	-13,197.72	-15,388.27	-8,964.01	-362.04	-13,073.97	-15,388.27	-8,978.11	-13,096.14	-15,388.27
Density (kg/m³)	1.2	22.1	0.4	0.8	2.7	861.1	3.5	1.1	2.3	861.1	63.6	2.3	861.1
V-L Molecular Weight	28.857	17.328	28.376	28.376	18.015	18.015	43.658	28.372	18.015	18.015	43.909	18.015	18.015
V-L Flowrate (lb-mol/hr)	47,764	1,935	49,755	49,755	5,783	5,783	1,857	45,173	44	44	1,839	3	3
V-L Flowrate (lb/hr)	1,378,307	33,530	1,411,837	1,411,837	104,189	104,189	81,080	1,281,661	799	799	80,757	47	47
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	80	1,156	332	308	305	86	87	420	305	85	400	305
Pressure (psia)	14.6	430.0	15.5	14.8	73.5	70.6	28.9	14.8	72.5	70.6	441.1	72.5	70.6
Steam Table Enthalpy (Btu/lb)[A]	13.2	9.5	358.2	135.7	1,192.4	273.2	16.5	37.8	1,245.6	273.2	-1.9	1,236.1	273.2
Aspen Plus Enthalpy (Btu/lb)[B]	-43.4	-1,929.1	-278.4	-500.9	-5,674.0	-6,615.8	-3,853.8	-155.6	-5,620.8	-6,615.8	-3,859.9	-5,630.3	-6,615.8
Density (lb/ft³)	0.076	1.380	0.025	0.049	0.166	53.757	0.218	0.071	0.141	53.757	3.971	0.145	53.757

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-3. Case 0 stream table, sorbent-based DAC system (continued)

	14	15	16	17	18	19	20	21	22	23	24	25	26
V-L Mole Fraction													
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0092	0.0092	0.0000	0.0000	0.0092	0.0000	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.9995	0.0500	0.9995	0.0000	0.0000	0.0000	0.0004	0.0004	0.0000	0.0000	0.0002	1.0000	1.0000
H_2O	0.0005	0.9500	0.0005	1.0000	1.0000	1.0000	0.0101	0.0101	1.0000	1.0000	0.0101	0.0000	0.0000
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7724	0.7724	0.0000	0.0000	0.7726	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2079	0.2079	0.0000	0.0000	0.2079	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	831	3	831	2,819	2,819	7,368	1,629,629	1,629,629	1,904	1,904	1,629,231	397	397
V-L Flowrate (kg/hr)	36,573	58	36,573	50,776	50,776	132,728	47,025,668	47,025,668	34,308	34,308	47,008,175	17,494	17,494
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	29	29	30	153	42	42	15	21	153	152	21	100	30
Pressure (MPa, abs)	2.90	3.04	15.27	0.51	0.01	0.01	0.10	0.11	0.51	0.49	0.10	0.10	15.27
Steam Table Enthalpy (kJ/kg)[A]	-6.32	137.79	-231.09	2,773.62	2,193.86	174.91	30.65	36.60	2,773.62	635.56	36.62	86.50	-231.33
Aspen Plus Enthalpy (kJ/kg)[B]	-8,969.87	-15,225.37	-9,194.65	-13,197.72	-13,777.49	-15,896.28	-100.93	-94.98	-13,197.72	-15,388.27	-91.67	-8,875.57	-9,193.41
Density (kg/m³)	60.1	375.2	630.1	2.7	0.1	977.6	1.2	1.3	2.7	861.1	1.2	1.5	628.8
V-L Molecular Weight	43.997	19.315	43.997	18.015	18.015	18.015	28.857	28.857	18.015	18.015	28.853	44.010	44.010
V-L Flowrate (lb-mol/hr)	1,833	7	1,833	6,214	6,214	16,243	3,592,716	3,592,716	4,199	4,199	3,591,840	876	876
V-L Flowrate (lb/hr)	80,630	127	80,630	111,942	111,942	292,615	103,673,852	103,673,852	75,637	75,637	103,635,285	38,567	38,567
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	85	85	86	308	107	107	59	70	308	305	70	212	86
Pressure (psia)	421.1	441.1	2,214.7	73.5	1.0	1.0	14.7	15.5	73.5	70.6	14.8	14.8	2,214.7
Steam Table Enthalpy (Btu/lb)[A]	-2.7	59.2	-99.4	1,192.4	943.2	75.2	13.2	15.7	1,192.4	273.2	15.7	37.2	-99.5
Aspen Plus Enthalpy (Btu/lb)[B]	-3,856.4	-6,545.7	-3,953.0	-5,674.0	-5,923.3	-6,834.2	-43.4	-40.8	-5,674.0	-6,615.8	-39.4	-3,815.8	-3,952.5
Density (lb/ft³)	3.755	23.421	39.338	0.166	0.004	61.031	0.076	0.079	0.166	53.757	0.075	0.091	39.252

[A]Steam table reference conditions are 32.02°F & 0.089 psia

[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Overall plant performance is summarized in Exhibit A-4; Exhibit A-5 provides a detailed breakdown of the auxiliary power requirements.

Exhibit A-4. Case 0 plant performance summary

Performance Summary	
Combustion Turbine Power, MWe	78
Steam Turbine Power, MWe	8
Total Gross Power, MWe	**86**
NGCC CO_2 Capture/Removal Auxiliaries, kWe	1,700
NGCC CO_2 Compression, kWe	2,810
DAC Air Fans, kWe	77,750
DAC CO_2 Compression, kWe	1,940
Balance of Plant, kWe	1,716
Total Auxiliaries, MWe	**86**
Net Power, MWe	**0**
NGCC HHV Net Plant Efficiency, %	36.1%
NGCC HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	9,981 (9,460)
HHV Combustion Turbine Efficiency, %	35.2%
NGCC LHV Net Plant Efficiency, %	40.0%
NGCC LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	9,008 (8,538)
LHV Combustion Turbine Efficiency, %	39.0%
Steam Turbine Cycle Efficiency, %	12.6%
Steam Turbine Heat Rate, kJ/kWh (Btu/kWh)	28,546 (27,057)
Condenser Duty, GJ/hr (MMBtu/hr)	123 (116)
NGCC CO_2 Capture System Cooling Duty, GJ/hr (MMBtu/hr)	221 (209)
Natural Gas Feed Flow, kg/hr (lb/hr)	15,209 (33,530)
HHV Thermal Input, kWt	220,930
LHV Thermal Input, kWt	199,411
NGCC Flue Gas CO_2 Captured, tonnes/yr	272,270
DAC CO_2 Removed from Air (Gross), tonnes/yr	130,260
NGCC Flue Gas CO_2 Emitted to Air, tonnes/yr	30,260
Net CO_2 Removed from Air, tonnes/yr	**100,000**

Exhibit A-5. Case 0 plant power summary

Power Summary	
Combustion Turbine Power, MWe	78
Steam Turbine Power, MWe	8
Total Gross Power, MWe	**86**
Auxiliary Load Summary	
Circulating Water Pumps, kWe	880
Combustion Turbine Auxiliaries, kWe	170
Condensate Pumps, kWe	5
Cooling Tower Fans, kWe	460
CO_2 Capture/Removal Auxiliaries, kWe	1,700
CO_2 Compression, kWe	2,810
Feedwater Pumps, kWe	20
Ground Water Pumps, kWe	80
Miscellaneous Balance of Plant,[A] kWe	70
SCR, kWe	1
Steam Turbine Auxiliaries, kWe	10
Transformer Losses, kWe	20
DAC Air Fans, kWe	77,750
DAC CO_2 Compression, kWe	1,940
Total DAC Auxiliaries, MWe	**80**
Total non-DAC Auxiliaries, MWe	**6**
Total Auxiliaries, MWe	**86**
Net Power, MWe	**0**

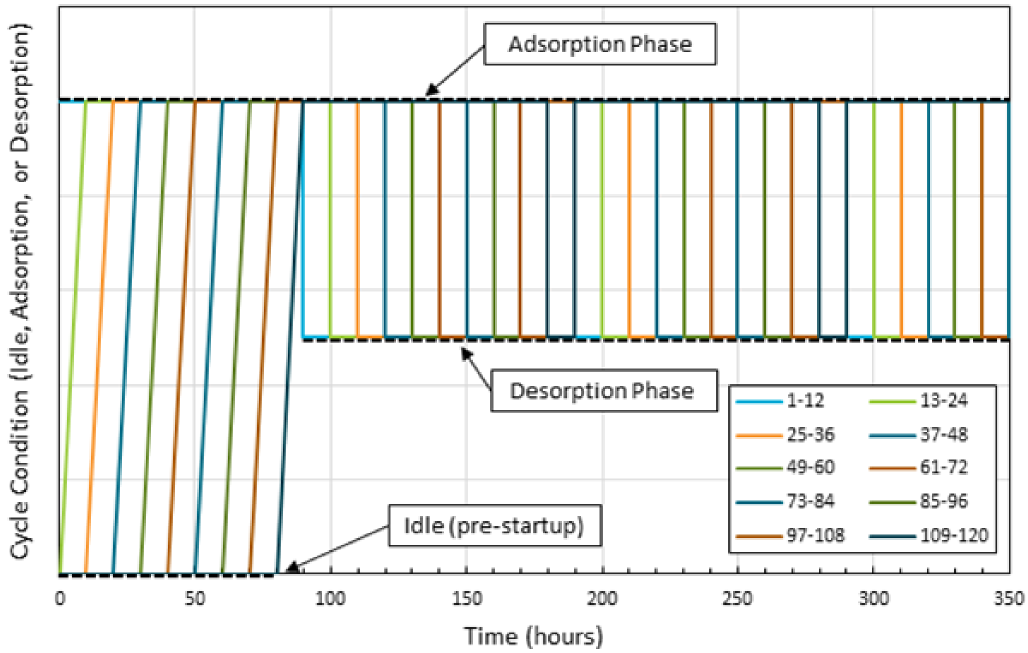
[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

A.2.2 Operational Profile

The DAC system is designed to operate similar to a semi-batch process. A total of 120 vessels are required for the performance assumptions (e.g., sorbent loading, bed depth and diameter, air velocity through the bed) and to meet the target net removal rate of 100,000 tonnes CO_2/yr (110,230 tons CO_2/yr). The 120 vessels are grouped into 10 blocks of 12 adsorber vessels. Every 10 hours a new block of adsorber vessels comes online; air flows through the vessel and the sorbent begins to adsorb CO_2. The vessels are staged such that each block is allowed a 90-hour adsorption cycle time. At the end of 90 hours, the air flow to the block is shut off, and steam flows through the inner heating coils of the adsorber to begin regeneration of the sorbent and production of CO_2. The regeneration cycle spans 10 hours, after which the block changes back to adsorption for 90 hours.

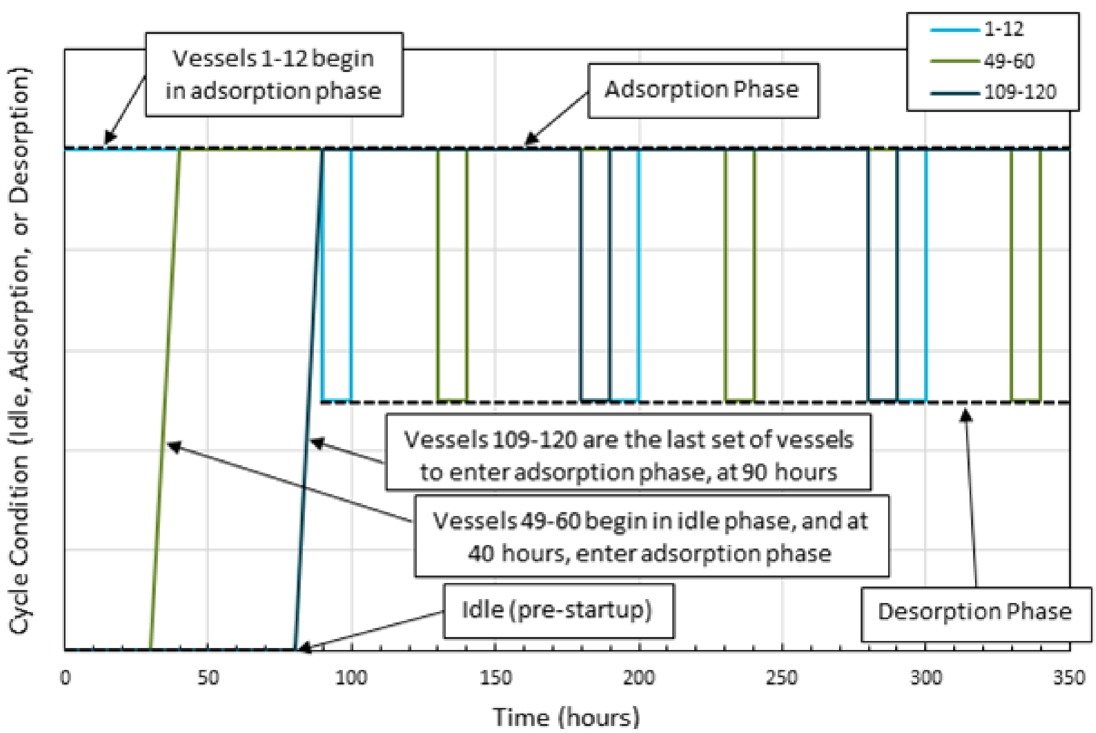
Exhibit A-6 shows the operational profile for all 10 blocks of Case 0 vessels, beginning at start-up of the facility through almost 3 complete desorption phases (3 complete cycles).

Exhibit A-6. DAC operational profile for all 10 blocks of vessels



A simplified operational profile for blocks 1, 5, and 10 only (vessels 1–12, 49–-60, and 109–120) is shown in Exhibit A-7.

Exhibit A-7. DAC operational profile for blocks 1, 5, and 10 (vessels 1-12, 49-60, and 109-120)



A.2.3 Environmental Performance

Exhibit A-8 presents a summary of the plant air emissions, which only include emissions from the NGCC plant and do not include emissions associated with CO_2-depleted air streams leaving the adsorber vessels.

Exhibit A-8. Case 0 air emissions

	kg/GJ (lb/MMBtu)	tonnes/yr (tons/yr)[A]	kg/MWh (lb/MWh)[B]	lb/lb $CO_{2\text{net captured}}$
SO_2	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
NOx	0.001 (0.003)	8 (9)	0.013 (0.028)	0.0001
Particulate	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
Hg	0.00E+0 (0.00E+0)	0.000 (0.000)	0.00E+0 (0.00E+0)	0.0000
CO	0.000 (0.000)	0 (0)	0.000 (0.000)	0.0000
CO_2	5 (12)	30,257 (33,353)	47 (104)	0.3026

[A]Calculations based on an 85 percent CF
[B]Emissions based on gross power

As discussed previously in Section 3.2, it is presently unclear to what environmental targets the DAC plant would be subject. However, based on the air emission targets laid out for reference NGCC power plants, Case 0 would comply with air emissions regulations for NGCC plants for SO_2 and NOx.

The natural gas was assumed to contain the domestic average value of total sulfur of 0.34 grains/100 scf (4.71×10^{-4} lb of sulfur/MMBtu). [18] It was also assumed that the added CH_4S was the sole contributor of sulfur to the natural gas. No sulfur capture systems were required.

The CT considered was based on the CT reported in NETL's BBR4 and scaled for the necessary output. [16] The reference CTs were designed to achieve approximately 1.8 ppmvd NOx emissions (at 15 percent O_2) using a dry LNB burner in the CT generator (CTG)—the dry LNB burners reduce the emissions to about 9 ppmvd (at 15 percent O_2) [27]—and selective catalytic reduction (SCR) equipment—the SCR system is designed for 86.7 percent NOx reduction. [28]

The pipeline natural gas was assumed to contain no Hg or HCl, resulting in zero emissions.

The reference CT at full scale emits approximately 1.0 ppmv CO. It was assumed that particulate matter (PM) emissions are zero. The production of PM is a result of system inefficiencies and is not produced or emitted in any significant amount.

Ninety percent of the CO_2 in the NGCC flue gas is removed in Shell's Cansolv facility. Sixty percent of the CO_2 in the DAC inlet air is removed by the sorbent in the DAC adsorber vessels.

The carbon balance for the plant is shown in Exhibit A-9. The carbon input to the plant consists of carbon in the natural gas and carbon as CO_2 in the air fed to both the CT and the DAC adsorber vessels. Carbon leaves the plant as CO_2 through the NGCC and DAC stacks, the NGCC and DAC CO_2 product streams, and other vents.

Exhibit A-9. Case 0 carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	10,985 (24,218)	NGCC Stack Gas	1,109 (2,445)
NGCC Air (CO_2)	105 (232)	NGCC CO_2 Product	9,979 (22,001)
DAC Air (CO_2)	7,957 (17,542)	NGCC CO_2 Dryer Vent	1.8 (3.9)
		NGCC CO_2 Knockout	0.0 (0.0)
		DAC CO_2 Product	4,774 (10,525)
		DAC Stack Gas	3,183 (7,017)
Total	**19,047 (41,992)**	**Total**	**19,047 (41,992)**

As shown in Exhibit A-10, the sulfur content of the natural gas is insignificant. All sulfur in the natural gas is assumed to react with Shell's Cansolv system solvent and is removed from the solvent during solvent reclaiming as a waste stream.

Exhibit A-10. Case 0 sulfur balance

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Natural Gas	0.2 (0.4)	Stack Gas	0.0 (0.0)
		Solvent Reclaiming	0.2 (0.4)
Total	**0.2 (0.4)**	**Total**	**0.2 (0.4)**

Exhibit A-11 shows the overall water balance for Case 0.

Exhibit A-11. Case 0 water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
CO_2 Drying	–	–	–	0.0 (0.3)	0.0 (-0.3)
CO_2 Capture System Makeup	0.0 (9.0)	–	0.0 (9.0)	–	0.0 (9.0)
CO_2 Capture Recovery	–	–	–	0.4 (98)	-0.4 (-98)
CO_2 Compression Recovery	–	–	–	0.0 (0.6)	0.0 (-0.6)
Cooling Tower	3.4 (893)	–	3.4 (893)	0.8 (201)	2.6 (692)
Total	3.4 (902)	–	3.4 (902)	1.1 (300)	2.3 (602)

A.2.4 Energy and Mass Balance Diagrams

An energy and mass balance diagram is shown for the NGCC in Exhibit A-12. An overall plant energy balance is provided in tabular form in Exhibit A-13.

The cooling tower load includes the condenser, capture process heat rejected to cooling water, the CO_2 compressor intercooler load for both compressors, and other miscellaneous cooling loads.

Exhibit A-12. Case 0 energy and mass balance, sorbent-based DAC system

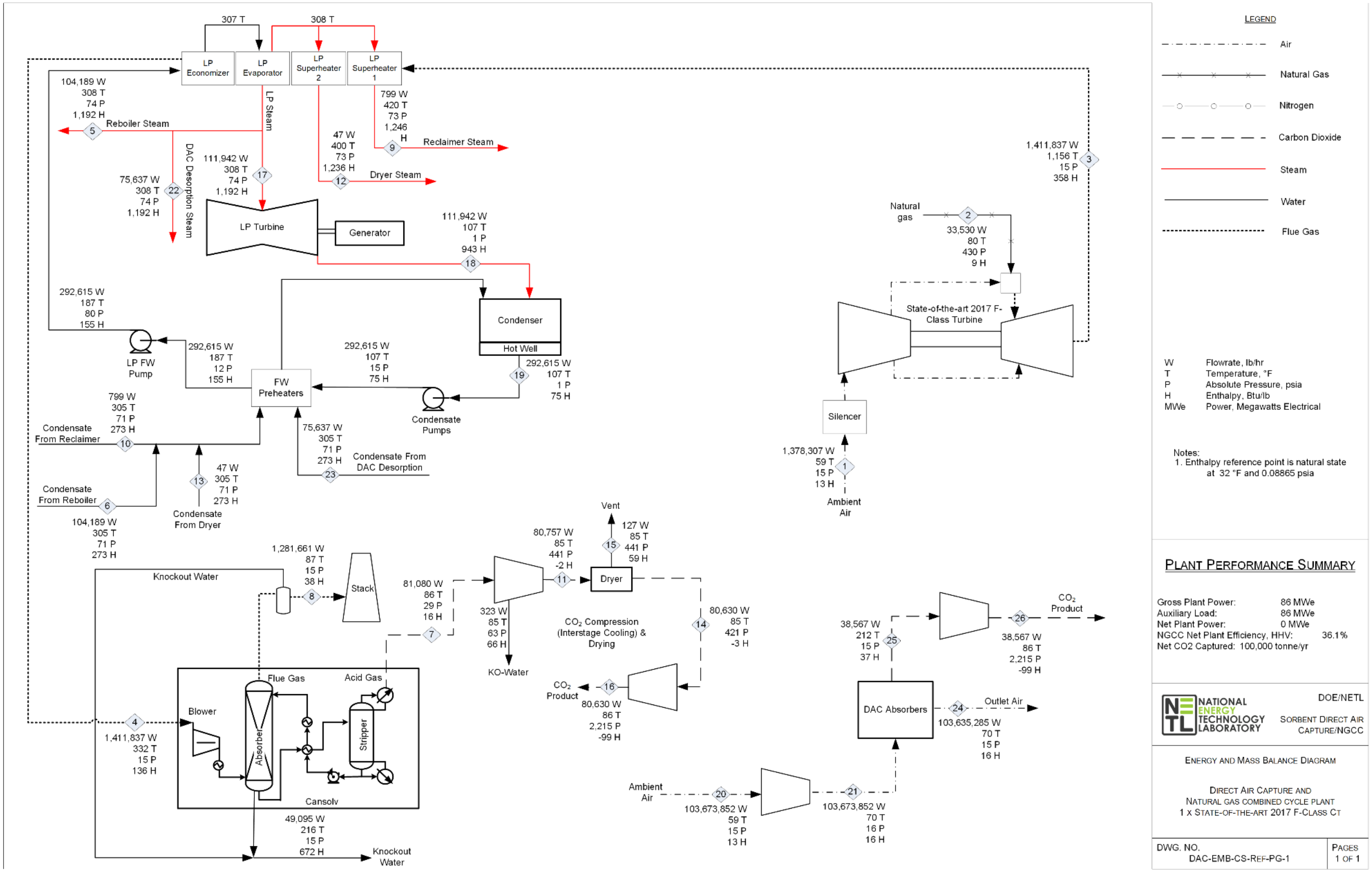


Exhibit A-13. Case 0 overall energy balance (0 °C [32 °F] reference)

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
Natural Gas	795 (754)	0.5 (0.5)	–	796 (754)
NGCC Air	–	19 (18)	–	19 (18)
DAC Air	–	1,441 (1,366)	–	1,441 (1,366)
Raw Water Makeup	–	13 (12)	–	13 (12)
Auxiliary Power	–	–	309 (293)	309 (293)
Total	**795 (754)**	**1,474 (1,397)**	**309 (293)**	**2,578 (2,444)**
Heat Out GJ/hr (MMBtu/hr)				
NGCC Stack Gas	–	51 (48)	–	51 (48)
DAC Stack Gas	–	1,721 (1,632)	–	1,721 (1,632)
Sulfur	–	–	–	0.0 (0.0)
Motor Losses and Design Allowances	–	–	7.4 (7.0)	7.4 (7.0)
Cooling Tower Load[A]	–	441 (418)	–	441 (418)
NGCC CO_2 Product Stream	–	-8.5 (-8.0)	–	-8.5 (-8.0)
Deaerator Vent	–	–	–	0.0 (0.0)
DAC CO_2 Product Stream	–	-4.0 (-3.8)	–	-4.0 (-3.8)
Ambient Losses[B]	–	*4.4 (4.2)*	–	*4.4 (4.2)*
Power	–	–	309 (293)	309 (293)
Total	**–**	**2,210 (2,091)**	**317 (300)**	**2,527 (2,391)**
Unaccounted Energy[C]	**–**	***56(53)***	–	*56 (53)*

[A]Includes condenser, capture process cooling loads, CO_2 compression intercooling loads, and miscellaneous cooling loads
[B]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the combustor, superheater, and transformers
[C]By difference

A.2.5 Case 0 – Equipment List

Major equipment items for the total plant (NGCC plant with CO_2 capture and DAC system) are shown in the following tables. The accounts used in the equipment list correspond to the account numbers used in the cost estimates in Section A.2.6. In general, the design conditions include a 10 percent contingency for flows and heat duties and a 21 percent contingency for heads on pumps and fans.

Case 0 – Account 3: Feedwater and Miscellaneous Balance of Plant Systems

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Condensate Pumps	Vertical canned	2,450 lpm @ 10 m H_2O (650 gpm @ 40 ft H_2O)	1	1
2	Boiler Feedwater Pump	Horizontal, split case, multi-stage, centrifugal, with interstage bleed for IP and LP feedwater	LP water: 2,450 lpm @ 60 m H_2O (650 gpm @ 190 ft H_2O)	2	2
3	Auxiliary Boiler	Shop fabricated, water tube	18,000 kg/hr, 2.8 MPa, 343°C (40,000 lb/hr, 400 psig, 650°F)	1	0
4	Service Air Compressors	Flooded screw	13 m^3/min @ 0.7 MPa (450 scfm @ 100 psig)	2	1
5	Instrument Air Dryers	Duplex, regenerative	13 m^3/min (450 scfm)	2	1
6	Closed Cycle Cooling Heat Exchangers	Plate and frame	13 MMkJ/hr (13 MMBtu/hr)	2	0
7	Closed Cycle Cooling Water Pumps	Horizontal centrifugal	5,200 lpm @ 20 m H_2O (1,400 gpm @ 70 ft H_2O)	2	1
8	Engine-Driven Fire Pump	Vertical turbine, diesel engine	3,785 lpm @ 110 m H_2O (1,000 gpm @ 350 ft H_2O)	1	1
9	Fire Service Booster Pump	Two-stage horizontal centrifugal	2,650 lpm @ 80 m H_2O (700 gpm @ 250 ft H_2O)	1	1
10	Raw Water Pumps	Stainless steel, single suction	1,800 lpm @ 20 m H_2O (500 gpm @ 60 ft H_2O)	2	1
11	Filtered Water Pumps	Stainless steel, single suction	170 lpm @ 50 m H_2O (50 gpm @ 160 ft H_2O)	2	1
12	Filtered Water Tank	Vertical, cylindrical	164,000 liter (43,000 gal)	1	0
13	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly and electro-deionization unit	370 lpm (100 gpm)	1	0
14	Liquid Waste Treatment System	–	10 years, 24-hour storm	1	0
15	Gas Pipeline	Underground, coated carbon steel, wrapped cathodic protection	13 m^3/min @ 3.0 MPa (445 acfm @ 430 psia) 39 cm (16 in) standard wall pipe	16 km (10 mile)	0
16	Gas Metering Station	–	13 m^3/min (445 acfm)	1	0

Case 0 – Account 5: Flue Gas Cleanup

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Shell's Cansolv System	Amine-based CO_2 capture technology	704,000 kg/hr (1,553,000 lb/hr) 6.3 wt% CO_2 concentration	1	0
2	Shell's Cansolv LP Condensate Pump	Centrifugal	871 lpm @ 5 m H_2O (230 gpm @ 17 ft H_2O)	1	1
3	Shell's Cansolv HP Condensate Pump	Centrifugal	7 lpm @ 5 m H_2O (2 gpm @ 17 ft H_2O)	1	1
4	CO_2 Dryer	Triethylene glycol	Inlet: 10 m^3/min @ 3.0 MPa (339 acfm @ 441 psia) Outlet: 2.9 MPa (421 psia) Water Recovered: 58 kg/hr (127 lb/hr)	1	0
5	CO_2 Compressor	Integrally geared, multi-stage centrifugal	1.0 m^3/min @ 15.3 MPa, 80°C (38 acfm @ 2,217 psia, 176°F)	1	0
6	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15.3 MPa, 30°C (2,215 psia, 86°F) Duty: 6 MMkJ/hr (5 MMBtu/hr)	1	0

Case 0 – Account 6: Combustion Turbine and Accessories

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Combustion Turbine	Advanced F class w/ dry low-NOx burner	80 MW	1	0
2	Combustion Turbine Generator	Hydrogen Cooled	90 MVA @ 0.9 p.f., 18 kV, 60 Hz, 3-phase	1	0

Case 0 – Account 7: HRSG, Ductwork, and Stack

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Stack	CS plate, type 409SS liner	46 m (150 ft) high x 2.8 m (9 ft) diameter	1	0
2	Heat Recovery Steam Generator	Drum, single-pressure with economizer section	Main steam - 146,001 kg/hr, 0.4 MPa/153°C (321,876 lb/hr, 59 psig/308°F)	1	0
3	SCR Reactor	–	640,000 kg/hr (1,410,000 lb/hr)	1	0
4	SCR Catalyst	–	Space available for an additional catalyst layer	1 layer	0
5	Dilution Air Blowers	Centrifugal	2.0 m³/min @ 108 cm WG (70 scfm @ 42 in WG)	1	1
6	Ammonia Feed Pump	Centrifugal	0.4 lpm @ 90 m H_2O (0.1 gpm @ 300 ft H_2O)	1	1
7	Ammonia Storage Tank	Horizontal tank	6,000 liter (2,000 gal)	1	0

Case 0 – Account 8: Steam Turbine and Accessories

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	8 MW 0.4 MPa/153°C/153°C (59 psig/ 308°F/308°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	10 MVA @ 0.9 p.f., 18 kV, 60 Hz, 3-phase	1	0
3	Surface Condenser	Two pass, divided waterbox including vacuum pumps and integrated deaerator	130 GJ/hr (130 MMBtu/hr), Inlet water temperature 16°C (60°F), Water temperature rise 11°C (20°F)	1	0
4	Steam Bypass	One per HRSG	50% steam flow @ design steam conditions	1	0

Case 0 – Account 9: Cooling Water System

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	87,000 lpm @ 30 m (23,000 gpm @ 100 ft)	2	1
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (51.5°F) wet bulb/ 16°C (60°F) CWT/ 27°C (80°F) HWT/ 490 GJ/hr (460 MMBtu/hr) heat duty	1	0

Case 0 – Account 11: Accessory Electric Plant

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Medium Voltage Transformer	Oil-filled	18 kV/4.16 kV, 3 MVA, 3-ph, 60 Hz	1	1
2	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 1 MVA, 3-ph, 60 Hz	1	1

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
3	CTG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	18 kV, 3-ph, 60 Hz	1	0
4	STG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	18 kV, 3-ph, 60 Hz	1	0
5	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
6	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
7	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Case 0 – Account 12: Instrumentation and Control

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser, color); Engineering printer (laser, black and white)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

Case 0 – Account 15: Direct Air Capture

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Absorbers	Sorbent, packed bed	431,000 kg/hr (950,000 lb/hr) 0.06 wt% CO_2 concentration	120	0
2	Air Fans	-	862,279 kg/hr @ 0.1 MPa, (1,901,000 lb/hr @ 16 psia)	60	1
3	CO_2 Compressor	Reciprocating compressor	0.6 m^3/min @ 15.3 MPa, 118°C (18 acfm @ 2,215 psia, 244°F)	1	0
4	CO_2 Aftercooler	Shell and tube heat exchanger	Outlet: 15.3 MPa, 30°C (2,215 psia, 86°F) Duty: 4 MMkJ/hr (4 MMBtu/hr)	1	0

A.2.6 Case 0 – Cost Estimate Results

Exhibit A-14 shows a detailed breakdown of the capital costs; Exhibit A-15 shows the owner's costs, total overnight cost (TOC), and total as-spent cost (TASC); Exhibit A-16 shows the initial and annual operation and maintenance (O&M) costs; and Exhibit A-17 shows the COC breakdown. The capital cost estimate presented represents an AACE International (AACE) Class 5 estimate, with an uncertainty range of +/-50 percent. Cost premiums that would be expected for first-of-a-kind technologies (e.g., various sorbent materials) are not reflected in the cost estimates. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required.

Exhibit A-14. Case 0 total plant cost details

Case:		DAC-0					Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	1					Sorbent Handling					
1.5	Sorbent Receive & Unload	$99	$0	$30	$0	$128	$26	$0	$23	$177	$2
1.6	Sorbent Stackout & Reclaim	$739	$0	$134	$0	$873	$175	$0	$157	$1,205	$12
1.7	Sorbent Conveyors	$1,106	$241	$268	$0	$1,614	$323	$0	$291	$2,228	$22
1.8	Other Sorbent Handling	$54	$13	$28	$0	$94	$19	$0	$17	$130	$1
1.9	Sorbent Handling Foundations	$0	$707	$932	$0	$1,639	$328	$0	$295	$2,262	$23
	Subtotal	$1,999	$960	$1,391	$0	$4,349	$870	$0	$783	$6,002	$60
	2					Sorbent Preparation and Feed					
2.5	Sorbent Preparation Equipment	$491	$21	$101	$0	$613	$123	$0	$110	$846	$8
2.6	Sorbent Storage & Feed	$823	$0	$310	$0	$1,134	$227	$0	$204	$1,565	$16
2.9	Sorbent Feed Foundation	$0	$330	$290	$0	$620	$124	$0	$112	$855	$9
	Subtotal	$1,315	$351	$701	$0	$2,366	$473	$0	$426	$3,266	$33
	3					Feedwater and Miscellaneous BOP Systems					
3.1	Feedwater System	$659	$1,129	$565	$0	$2,352	$470	$0	$423	$3,246	$32
3.2	Water Makeup & Pretreating	$1,493	$149	$846	$0	$2,488	$498	$0	$597	$3,582	$36
3.3	Other Feedwater Subsystems	$375	$123	$117	$0	$614	$123	$0	$111	$848	$8
3.4	Service Water Systems	$453	$865	$2,800	$0	$4,118	$824	$0	$988	$5,930	$59
3.5	Other Boiler Plant Systems	$78	$28	$71	$0	$178	$36	$0	$32	$245	$2
3.6	Natural Gas Pipeline and Start-Up System	$4,843	$208	$156	$0	$5,208	$1,042	$0	$937	$7,187	$72
3.7	Waste Water Treatment Equipment	$2,793	$0	$1,712	$0	$4,505	$901	$0	$1,081	$6,487	$65
3.8	Open	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
3.9	Miscellaneous Plant Equipment	$6,018	$789	$3,059	$0	$9,866	$1,973	$0	$2,368	$14,207	$142
	Subtotal	$16,712	$3,292	$9,325	$0	$29,329	$5,866	$0	$6,538	$41,733	$417
	5					Flue Gas Cleanup					
5.1	Shell's Cansolv CO_2 Removal System	$46,504	$24,476	$51,400	$0	$122,380	$24,476	$22,028	$33,777	$202,661	$2,027
5.4	CO_2 Compression & Drying	$12,611	$1,892	$5,232	$0	$19,734	$3,947	$0	$4,736	$28,417	$284
5.5	CO_2 Compressor Aftercooler	$80	$13	$34	$0	$127	$25	$0	$30	$183	$2
5.12	Gas Cleanup Foundations	$0	$91	$98	$0	$190	$38	$0	$45	$273	$3
	Subtotal	$59,195	$26,471	$56,764	$0	$142,430	$28,486	$22,028	$38,589	$231,534	$2,315
	6					Combustion Turbine and Accessories					
6.1	Combustion Turbine Generator	$24,745	$0	$1,506	$0	$26,251	$5,250	$0	$4,725	$36,226	$362

Case:		DAC-0						Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000						Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
6.3	Combustion Turbine Accessories	$900	$0	$55	$0	$954	$191	$0	$172	$1,317	$13
6.4	Compressed Air Piping	$0	$297	$67	$0	$364	$73	$0	$66	$503	$5
6.5	Combustion Turbine Foundations	$0	$310	$335	$0	$646	$129	$0	$155	$930	$9
	Subtotal	$25,644	$607	$1,963	$0	$28,215	$5,643	$0	$5,117	$38,975	$390
	7					HRSG, Ductwork, and Stack					
7.1	Heat Recovery Steam Generator	$8,665	$0	$2,166	$0	$10,831	$2,166	$0	$1,950	$14,946	$149
7.2	Heat Recovery Steam Generator Accessories	$830	$0	$154	$0	$984	$197	$0	$177	$1,358	$14
7.3	Ductwork	$0	$239	$166	$0	$405	$81	$0	$73	$559	$6
7.4	Stack	$2,284	$0	$424	$0	$2,708	$542	$0	$487	$3,737	$37
7.5	Heat Recovery Steam Generator, Ductwork & Stack Foundations	$0	$178	$167	$0	$345	$69	$0	$83	$497	$5
7.6	Selective Catalytic Reduction System	$580	$244	$340	$0	$1,163	$233	$0	$209	$1,605	$16
	Subtotal	$12,359	$661	$3,417	$0	$16,437	$3,287	$0	$2,979	$22,703	$227
	8					Steam Turbine and Accessories					
8.1	Steam Turbine Generator & Accessories	$1,832	$0	$268	$0	$2,100	$420	$0	$378	$2,898	$29
8.2	Steam Turbine Plant Auxiliaries	$12	$0	$26	$0	$37	$7	$0	$7	$52	$1
8.3	Condenser & Auxiliaries	$953	$0	$510	$0	$1,463	$293	$0	$263	$2,018	$20
8.4	Steam Piping	$1,364	$0	$553	$0	$1,916	$383	$0	$345	$2,644	$26
8.5	Turbine Generator Foundations	$0	$98	$162	$0	$260	$52	$0	$62	$374	$4
	Subtotal	$4,160	$98	$1,519	$0	$5,776	$1,155	$0	$1,055	$7,987	$80
	9					Cooling Water System					
9.1	Cooling Towers	$3,236	$0	$980	$0	$4,215	$843	$0	$759	$5,817	$58
9.2	Circulating Water Pumps	$434	$0	$27	$0	$460	$92	$0	$83	$635	$6
9.3	Circulating Water System Auxiliaries	$4,413	$0	$582	$0	$4,996	$999	$0	$899	$6,894	$69
9.4	Circulating Water Piping	$0	$1,086	$984	$0	$2,070	$414	$0	$373	$2,856	$29
9.5	Make-up Water System	$183	$0	$235	$0	$417	$83	$0	$75	$576	$6
9.6	Component Cooling Water System	$160	$0	$123	$0	$283	$57	$0	$51	$390	$4
9.7	Circulating Water System Foundations	$0	$251	$417	$0	$668	$134	$0	$160	$963	$10
	Subtotal	$8,425	$1,337	$3,347	$0	$13,110	$2,622	$0	$2,400	$18,131	$181
	10					Spent Sorbent Handling System					
10.6	Ash Spent Sorbent Storage Silos	$537	$0	$1,641	$0	$2,178	$436	$0	$392	$3,005	$30

Case:		DAC-0						Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000						Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies			Total Plant Cost	
				Direct	Indirect			Process	Project		$/1,000	$/tonne (net)
10.7	Ash Spent Sorbent Transport & Feed Equipment	$1,824	$0	$1,809	$0	$3,633	$727	$0	$654		$5,014	$50
10.9	Ash/Spent Sorbent Foundation	$0	$374	$459	$0	$832	$166	$0	$200		$1,198	$12
	Subtotal	$2,361	$374	$3,909	$0	$6,643	$1,329	$0	$1,246		$9,217	$92
	11					Accessory Electric Plant						
11.1	Generator Equipment	$722	$0	$545	$0	$1,267	$253	$0	$228		$1,749	$17
11.2	Station Service Equipment	$1,788	$0	$153	$0	$1,942	$388	$0	$350		$2,680	$27
11.3	Switchgear & Motor Control	$2,554	$0	$433	$0	$2,997	$599	$0	$539		$4,315	$41
11.4	Conduit & Cable Tray	$0	$617	$1,778	$0	$2,395	$479	$0	$431		$3,306	$33
11.5	Wire & Cable	$0	$921	$1,647	$0	$2,568	$514	$0	$462		$3,544	$35
11.6	Protective Equipment	$44	$0	$153	$0	$197	$39	$0	$35		$272	$3
11.7	Standby Equipment	$231	$0	$214	$0	$445	$89	$0	$80		$614	$6
11.8	Main Power Transformers	$350	$0	$7	$0	$357	$71	$0	$64		$493	$5
11.9	Electrical Foundations	$0	$21	$53	$0	$73	$15	$0	$18		$106	$1
	Subtotal	$5,690	$1,559	$4,993	$0	$12,242	$2,448	$0	$2,208		$16,898	$169
	12					Instrumentation and Control						
12.1	Natural Gas Combined Cycle Control Equipment	$186	$0	$118	$0	$304	$61	$0	$55		$420	$4
12.2	Combustion Turbine Control Equipment	$306	$0	$195	$0	$501	$100	$0	$90		$691	$7
12.3	Steam Turbine Control Equipment	$298	$0	$190	$0	$488	$98	$0	$88		$673	$7
12.4	Other Major Component Control Equipment	$471	$0	$300	$0	$772	$154	$39	$145		$1,109	$11
12.5	Signal Processing Equipment	$417	$0	$13	$0	$430	$86	$0	$77		$593	$6
12.6	Control Boards, Panels & Racks	$104	$0	$63	$0	$167	$33	$8	$31		$240	$2
12.7	Distributed Control System Equipment	$5,777	$0	$177	$0	$5,953	$1,191	$298	$1,116		$8,558	$86
12.8	Instrument Wiring & Tubing	$477	$382	$1,526	$0	$2,385	$477	$119	$447		$3,428	$34
12.9	Other Instrumentation & Controls Equipment	$330	$0	$765	$0	$1,095	$219	$55	$205		$1,575	$16
	Subtotal	$8,366	$382	$3,348	$0	$12,095	$2,419	$519	$2,255		$17,287	$173
	13					Improvements to Site						
13.1	Site Preparation	$0	$212	$4,509	$0	$4,721	$944	$0	$1,133		$6,798	$68
13.2	Site Improvements	$0	$683	$903	$0	$1,585	$317	$0	$381		$2,283	$23
13.3	Site Facilities	$655	$0	$688	$0	$1,343	$269	$0	$322		$1,934	$19

Case:		DAC-0					Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	Subtotal	$655	$895	$6,099	$0	$7,650	$1,530	$0	$1,836	$11,015	$110
	14					Buildings and Structures					
14.1	Combustion Turbine Area	$0	$176	$93	$0	$270	$54	$0	$49	$372	$4
14.3	Steam Turbine Building	$0	$430	$572	$0	$1,001	$200	$0	$180	$1,382	$14
14.4	Administration Building	$0	$173	$117	$0	$290	$58	$0	$52	$400	$4
14.5	Circulation Water Pumphouse	$0	$20	$10	$0	$30	$6	$0	$5	$41	$0
14.6	Water Treatment Buildings	$0	$136	$124	$0	$260	$52	$0	$47	$358	$4
14.7	Machine Shop	$0	$253	$162	$0	$415	$83	$0	$75	$573	$6
14.8	Warehouse	$0	$206	$124	$0	$330	$66	$0	$59	$455	$5
14.9	Other Buildings & Structures	$0	$183	$132	$0	$315	$63	$0	$57	$435	$4
14.10	Waste Treating Building & Structures	$0	$346	$619	$0	$965	$193	$0	$174	$1,332	$13
	Subtotal	$0	$1,923	$1,953	$0	$3,876	$775	$0	$698	$5,349	$53
	15					Direct Air Capture System					
15.1	DAC Adsorption/Desorption Vessels	$0	$31,417	$25,705	$0	$57,121	$11,424	$5,712	$11,139	$85,396	$854
15.2	DAC CO_2 Compression & Drying	$2,406	$361	$998	$0	$3,765	$753	$376	$734	$5,628	$56
15.3	DAC CO_2 Compressor Aftercooler	$86	$14	$37	$0	$137	$27	$0	$25	$189	$2
15.4	DAC System Air Handling Duct and Dampers	$7,275	$29,100	$12,125	$0	$48,500	$9,700	$4,850	$9,457	$72,507	$725
15.5	DAC System Air Handling Fans	$83,404	$0	$4,390	$0	$87,794	$17,559	$8,779	$17,120	$131,252	$1,313
15.6	DAC Desorption Process Gas Handling System	$178	$758	$249	$0	$1,185	$237	$118	$231	$1,771	$18
15.7	DAC Steam Distribution System	$529	$2,256	$740	$0	$3,525	$705	$353	$687	$5,270	$53
15.8	DAC System Controls Equipment	$400	$0	$255	$0	$656	$131	$66	$128	$980	$10
	Subtotal	**$94,278**	**$63,906**	**$44,498**	**$0**	**$202,682**	**$40,536**	**$20,255**	**$39,521**	**$302,994**	**$3,030**
	Total	**$241,158**	**$102,816**	**$143,225**	**$0**	**$487,200**	**$97,440**	**$42,802**	**$105,651**	**$733,092**	**$7,331**

Exhibit A-15. Case 0 owner's costs

Description	$/1,000	$/tonne
Pre-Production Costs		
6 Months All Labor	$5,674	$57
1-Month Maintenance Materials	$819	$8
1-Month Non-Fuel Consumables	$1,338	$13
1-Month Waste Disposal	$245	$2
25% of 1 Month's Fuel Cost at 100% CF	$608	$6
2% of TPC	$14,662	$147
Total	**$23,347**	**$233**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$2,602	$26
0.5% of TPC (spare parts)	$3,665	$37
Total	**$6,267**	**$63**
Other Costs		
Initial Cost for Catalyst and Chemicals	$6,924	$69
Land	$156	$2
Other Owner's Costs	$109,964	$1,100
Financing Costs	$19,793	$198
Total Overnight Costs (TOC)	**$899,543**	**$8,995**
TASC Multiplier (IOU, 33 year)	1.093	
Total As-Spent Cost (TASC)	**$982,883**	**$9,829**

Exhibit A-16. Case 0 initial and annual operating and maintenance costs

Case:	**DAC-0**	**Sorbent DAC w/ 1x1 NGCC w/ CO_2 Capture**			**Cost Base:**	**September 2019**
Plant Size:	**100,000**	**tonnes of CO_2 captured (net)**			**Capacity Factor (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	3.0	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	2.0	
				Lab Techs, etc.:	2.0	
				Total:	**8.0**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/tonne-net)**
Annual Operating Labor:					$3,507,504	$35
Maintenance Labor:					$5,571,499	$56
Administrative & Support Labor:					$2,269,751	$23
Property Taxes and Insurance:					$14,661,839	$147
Total:					**$26,010,593**	**$260**
Variable Operating Costs						
					($)	**($/tonne-net)**
Maintenance Material:					$8,357,248	$84
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	649	$1.90	$0	$382,725	$4
Makeup and Waste Water Treatment Chemicals (ton):	0	1.9	$550	$0	$330,024	$3
Ammonia (19 wt%, ton):	0	0.57	$300	$0	$52,832	$1
SCR Catalyst (ft³):	921	0.50	$150	$138,162	$23,487	$0
CO_2 Capture System Chemicals[A]	Proprietary				$1,189,867	$12
Triethylene Glycol (gal):	w/equip.	64	$6.80	$0	$135,684	$1
DAC Sorbent (ft³):	1,696,459	9,296	$4.00	$6,785,834	$11,535,918	$115
Subtotal:				**$6,923,996**	**$13,650,538**	**$137**
Waste Disposal						
SCR Catalyst (ft³):	0	0.50	$2.50	$0	$391	$0.0
Triethylene Glycol (gal):	0	64	$0.35	$0	$6,984	$0.1
Amine Purification Unit Waste (ton)	0	1	$38.00	$0	$11,747	$0.1
Thermal Reclaimer Unit Waste (ton)	0	0.089	$38.00	$0	$1,043	$0.0
DAC Sorbent (ft³):	0	9,296	$0.86	$0	$2,480,222	$24.8
Subtotal:				**$0**	**$2,500,389**	**$25.0**
Variable Operating Costs Total:				**$6,923,996**	**$24,508,175**	**$245**
Fuel Cost						
Natural Gas (MMBtu):	0	18,092	$4.42	$0	$24,811,118	$248
Total:				**$0**	**$24,811,118**	**$248**

[A]*CO_2 Capture System Chemicals* includes Ion Exchange Resin, NaOH, and Shell's Cansolv Solvent

A.2.7 Cost Estimate Scaling

The majority of Case 0's cost estimate was scaled using Case B31B from NETL's BBR4 as a reference. [16] Guidance on scaling the balance of sub-accounts that relate to Case B31B can be found in NETL's Quality Guidelines for Energy System Studies (QGESS): Capital Cost Scaling Methodology: Revision 4 Report. [29] Exceptions to this approach include costs for the HRSG (Case 0 considers a single pressure HRSG, whereas Case B31B considers a triple pressure reheat HRSG) and ST (similar to the HRSG, Case 0 only considers a low-pressure ST). Capital cost estimates for these accounts were developed by Black & Veatch using their in-house cost estimating references.

A.2.8 Cost of CO_2 Capture Results

Using the methodology presented in Section 3.6, Exhibit A-17 presents the results for the COC for Case 0.

Exhibit A-17. Case 0 COC

Component	COC DAC_{net}, \$/tonne	COC DAC_{gross}, \$/tonne	COC $Plant_{gross}$, \$/tonne
Capital	695.3	533.8	172.7
Fixed	260.1	199.7	64.6
Variable	245.1	188.1	60.9
Fuel	248.1	190.5	61.6
Total (Excluding T&S)	**1,448.6**	**1,112.1**	**359.9**
CO_2 T&S	40.3	30.9	10.0
Total (Including T&S)	**1,488.9**	**1,143.0**	**369.9**

For the COC DAC_{net} result of \$1,489/tonne CO_2 (\$1,351/ton CO_2) (including T&S), a total CO_2 flow of 100,000 tonnes/yr (110,230 tons CO_2/yr) is used. For the COC DAC_{gross} result of \$1,143/tonne CO_2 (\$1,037/ton CO_2) (including T&S), a total CO_2 flow of 130,260 tonnes/yr (143,587 tons/yr) is used. For the COC $Plant_{gross}$ result of \$370/tonne CO_2 (\$336/ton CO_2) (including T&S), a total CO_2 flow of 402,530 tonnes/yr (443,713 tons/yr) is used, which represents the gross CO_2 captured by the DAC system from the atmosphere (130,260 tonnes/yr) plus the CO_2 captured from Shell's Cansolv system for the NGCC plant (272,270 tonnes/yr).

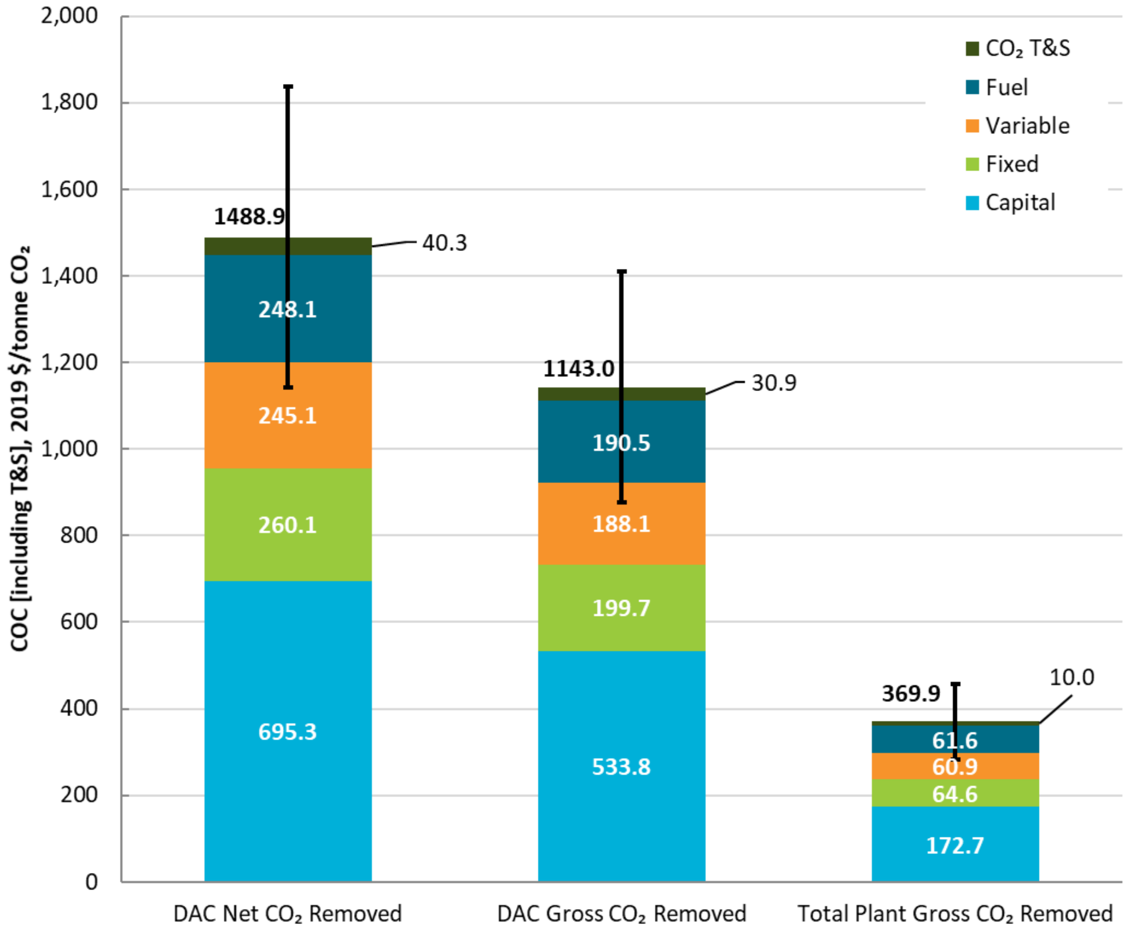
Exhibit A-18 presents the COC results graphically and includes error bars relating to the uncertainty in the capital cost estimate. The uncertainty of the capital cost estimates is +/-50 percent, consistent with Association for the Advancement of Cost Engineering (AACE) Class 5 cost estimates (i.e., concept screening), based on the level of engineering design performed. In all cases, this report relies on vendor cost estimates for component technologies and process equipment, corresponding to the assumption- and/or model-derived equipment specifications. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs, which can be a challenge for emerging technologies. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required. All costs are reported in 2019 dollars.

Sorbent-based direct air capture (DAC) systems are an immature technology, lacking a history of commercial deployment at scale. The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher the presented estimates. Absent demonstrated first-of-a-kind (FOAK) plant costs associated with a specific plant configuration/technology, it is difficult to explicitly project fully mature, N^{th}-of-a-kind (NOAK) values. Consequently, the cost estimates provided herein represent neither FOAK nor NOAK costs. Nevertheless, the application of a consistent methodology - and the presentation of detailed equipment specifications and costs based on contemporary sources - facilitate comparison between cases as well as sensitivity analyses to guide R&D, and generally improve upon many publicly available estimates characterized by more opaque methods and sources, and less detail.

Anticipated actual costs for projects based upon any of the cases presented herein 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 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.

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 here.

Exhibit A-18. Case 0 COC plot and uncertainty ranges



A.2.9 Sensitivity Analysis

The results of the literature review showed that there is limited information available for industrial-scale DAC systems. Several references present testing results for different materials that could have future application for DAC, but much of this work is performed at the bench scale. Similarly, there is limited information on the system configurations that would be applied, as much of the material performance results are obtained with bench-scale test set-ups. There is also limited work in the area of techno-economic analysis. Carbon Engineering presented techno-economic analysis results for their DAC system, but this system considers a solvent. [2] For the purposes of the present sorbent case study configuration, limited process data are available. Therefore, a sensitivity analysis was conducted on multiple process and cost parameters to gauge their impact on the final system performance and COC. The parameters of interest include capital cost (presented in Section A.2.8), natural gas price, sorbent cost, sorbent lifetime, financing assumptions (fixed charge rate [FCR]), system pressure drop, system capture fraction, sorbent regeneration energy, CF, and single cases addressing sorbent disposal cost and CO_2 product purity from the adsorber vessels. Exhibit A-19 summarizes the sensitivity study results such that the importance of different parameters can be weighed against each other.

Based on the reference Case 0 assumptions, and the parameter sensitivity ranges assumed, there is no case presented that would independently allow this DAC system to achieve a COC_{net} below \$1,000/tonne CO_2 (\$907/tonne CO_2). However, the cumulative effect of multiple sensitivity parameters rolled into a single case would result in a COC_{net} below this threshold. The packed bed pressure drop significantly impacts COC_{net} and it is concluded that a low pressure drop configuration must be considered. Case 0B, which assumes sorbent in the form of a monolith contactor, was developed to address this issue.

Exhibit A-19. Summary of COC sensitivity results

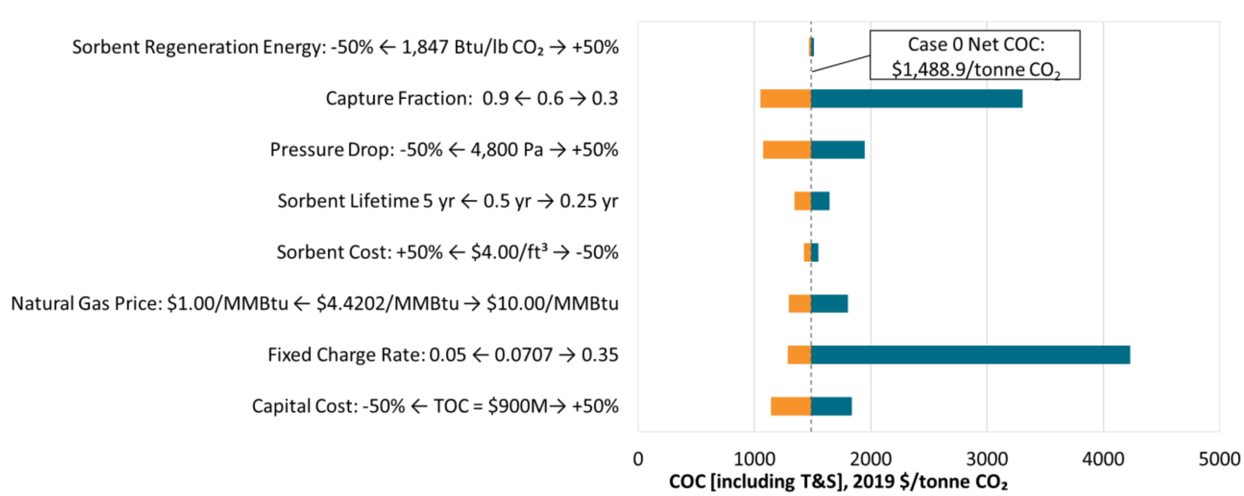
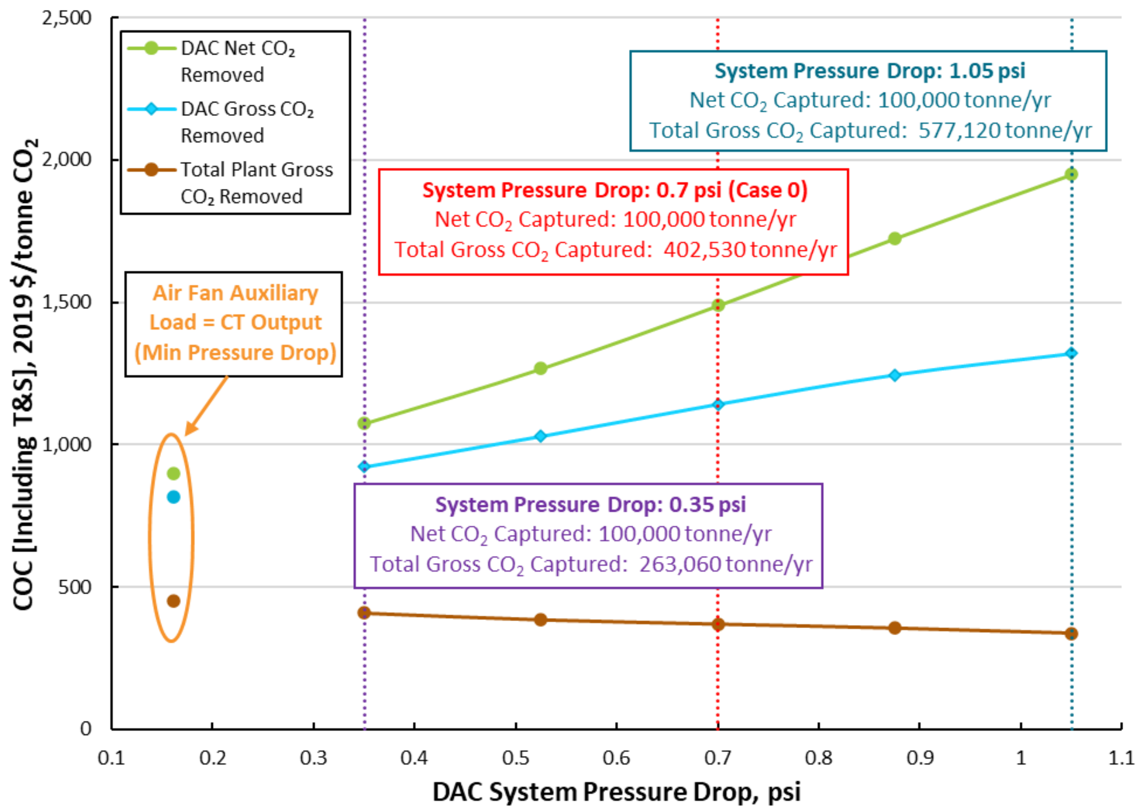


Exhibit A-20 shows the COC sensitivity to system pressure drop for the three different bases of calculation. Based on the assumptions regarding process configuration and adsorber vessel sizing parameters, Case 0 applied a DAC system pressure drop of 4.8 kPa (0.7 psi). This pressure drop specifically accounts for the air handling ducts from the air fan discharge to the adsorber vessel, through the adsorber sorbent bed, and discharging at the top of the adsorber vessel. The sensitivity range considered is +/-50 percent, and the COC shows about a 31 percent increase or 28 percent decrease at the endpoints of this range. Thus, pressure drop can have a large impact on the COC of the DAC system.

As the pressure drop changes, the amount of CO_2 that must be captured to maintain a net-negative CO_2 process (e.g., CO_2 removal from the atmosphere) changes significantly. For all pressure drop points shown, the target net CO_2 removed from the atmosphere is constant at 100,000 tonnes/yr (110,230 tons CO_2/yr). Case 0 requires that 402,530 tonnes CO_2/yr (443,713 tons CO_2/yr) (representing the sum of gross CO_2 removed by DAC plus CO_2 captured from the NGCC flue gas) be captured to obtain this net removal. When pressure drop increases by 50 percent to 7.2 kPa (1.05 psi), the total gross CO_2 that must be captured to obtain the target net removal from atmosphere increases by 43 percent, to 577,120 tonnes CO_2/yr (636,165 tons CO_2/yr). The opposite effect is observed when pressure drop is reduced.

Exhibit A-20. COC sensitivity to system pressure drop



An additional sensitivity regarding pressure drop was also investigated and is shown in Exhibit A-20 as three single points. The reference Case 0 was designed such that the HRSG produces enough excess steam such that the combined electrical output from the CT and ST is sufficient to satisfy the electrical auxiliary load of all of the plant equipment. These alternate cases demonstrate the total DAC system pressure drop that would need to be achieved such that the electrical output of only the CT would be sufficient to satisfy all plant electrical auxiliary loads, and the HRSG would only need to produce enough steam to satisfy the heating requirements of the DAC and Shell's Cansolv systems. In other words, excess steam to drive a steam bottoming cycle would not be produced. The pressure drop required for this case was determined to be approximately 1.1 kPa (0.16 psi), representing a 77 percent reduction from the Case 0 assumption of 4.8 kPa (0.7 psi). The resulting COC at this pressure drop is \$906/tonne CO_2, 39 percent less than Case 0.

Exhibit A-21 shows the cost of CO_2 capture (COC) sensitivity to natural gas price for the three different bases of calculation (DAC_{net}, DAC_{gross}, and Total $Plant_{Gross}$). The natural gas price is varied over the range of \$0.95/GJ (\$1/MMBtu—77 percent reduction from the reference) to \$9.5/GJ (\$10/MMBtu—126 percent increase from the reference). The results show that at the low natural gas price point, COC is reduced by 13 percent versus the reference, whereas, at the high natural gas price point, COC increases by 21 percent versus the reference. Fuel price accounts for approximately 17 percent of the COC (including T&S); therefore, COC is not overly sensitivity to the price of natural gas.

Exhibit A-21. COC sensitivity to natural gas price

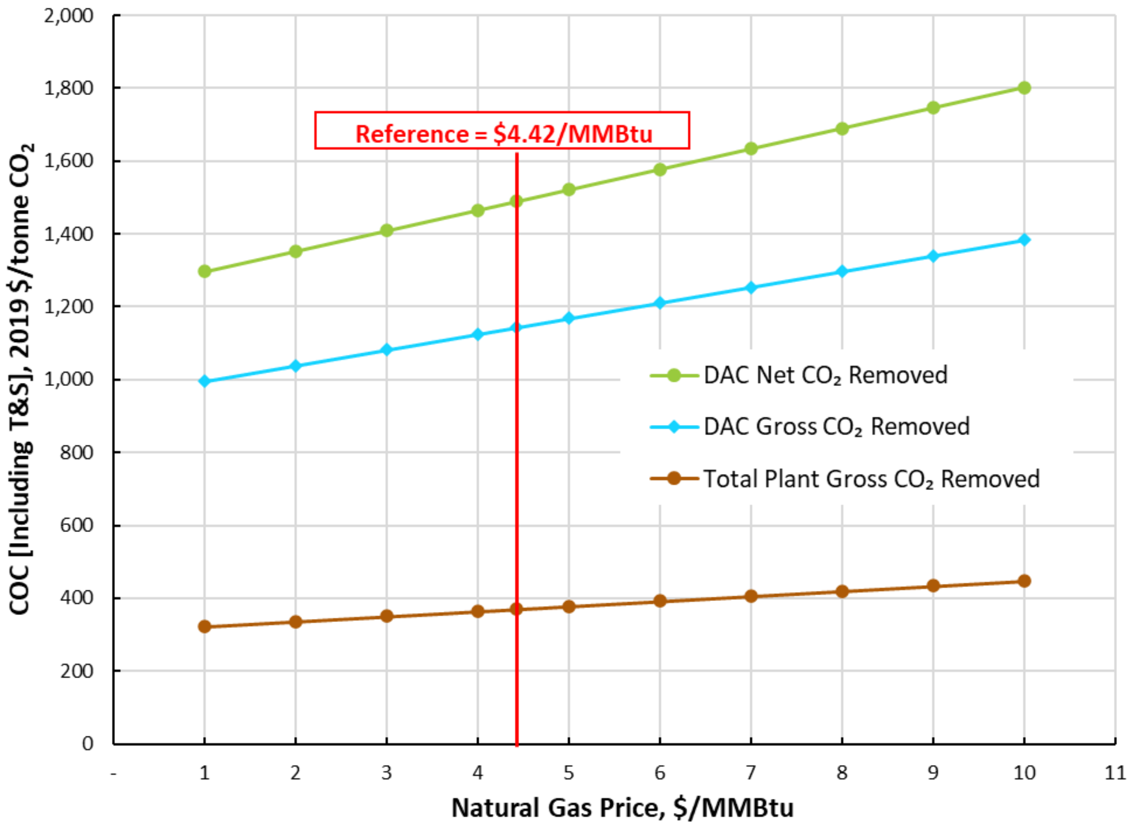


Exhibit A-22 shows the COC sensitivity to sorbent cost for the three different bases of calculation. Due to lack of data, there was limited information available to inform the reference Case 0 assumption of $4.00/ft^3 ($0.09/lb) sorbent cost. The sorbent cost range considered is +/- 50 percent around the reference sorbent cost. The maximum and minimum parameter ranges result in only a 4 percent increase or decrease in the COC. For Case 0, variable O&M accounts for only 16 percent of the COC. Of this 16 percent, the annual sorbent make-up cost accounts for 47 percent of the variable O&M; therefore, within this price range, the sorbent cost is found to be a relatively non-impactful parameter in terms of COC.

Exhibit A-22. COC sensitivity to sorbent cost

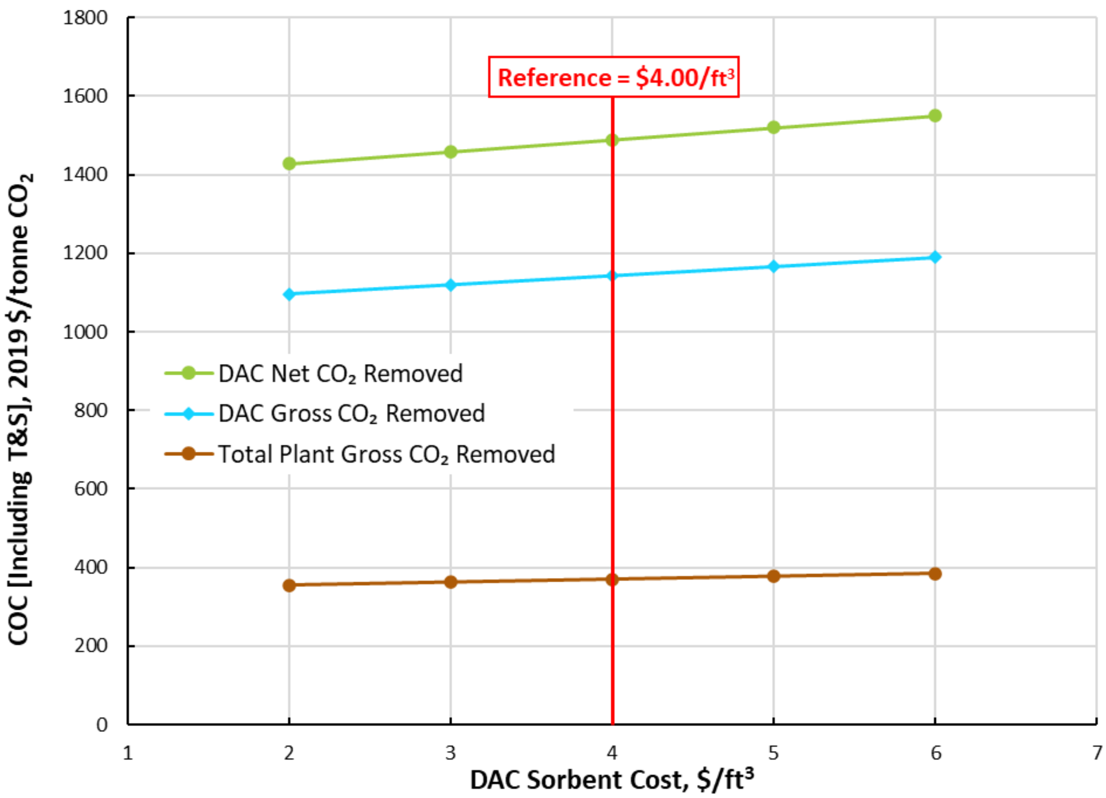


Exhibit A-23 shows the COC sensitivity to sorbent lifetime for the three different bases of calculation. The reference Case 0 assumes that the sorbent life is 6 months. Due to lack of data, there was limited information available to inform this assumption. The sensitivity range is -50 percent (3 months) to +900 percent (5 years), and the COC shows about a 10 percent increase or decrease at the endpoints of this range. At a sorbent lifetime of approximately 2 years, the COC trend begins to level out, with minimal reductions in COC as the sorbent lifetime extends from 2 years to 5 years (~2 percent reduction in COC from 2- to 5-year sorbent lifetime).

Exhibit A-23. COC sensitivity to sorbent lifetime

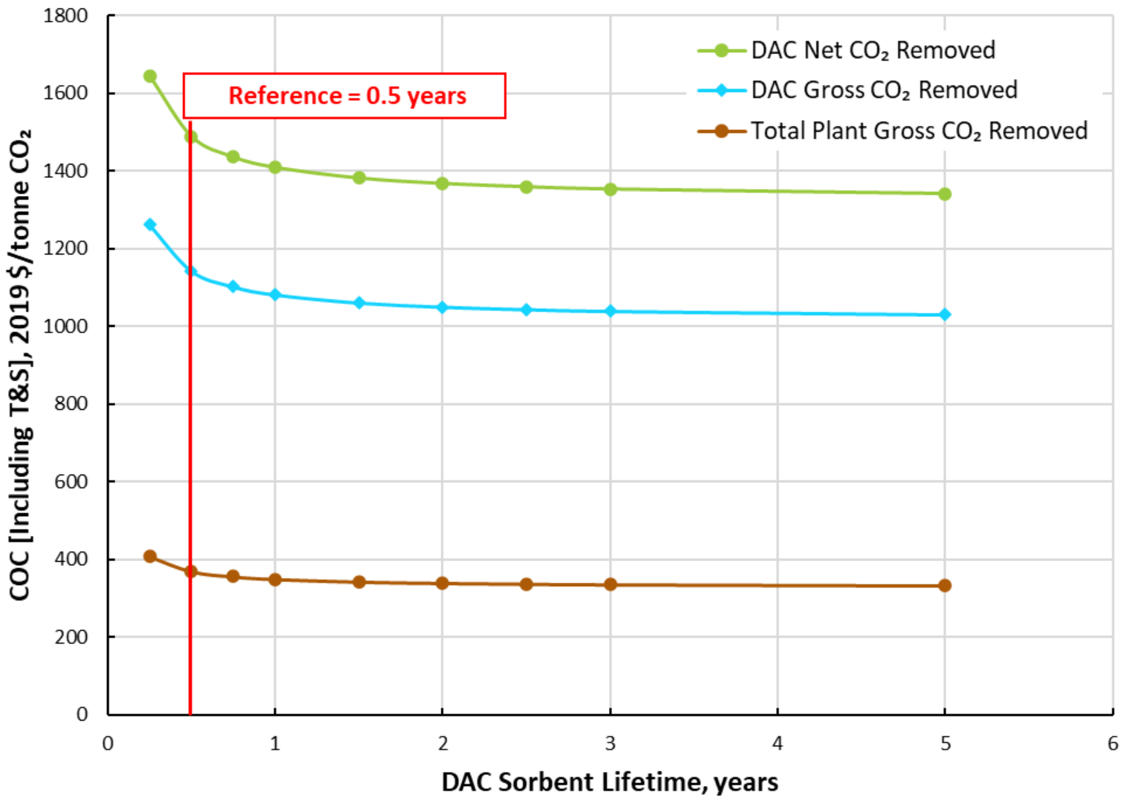


Exhibit A-24 shows the COC sensitivity to FCR for the three different bases of calculation. The reference Case 0 assumes an FCR of 0.0707, which is the value used for NGCC plant levelized cost of electricity (LCOE) calculations as discussed previously in Section 3.6. This value was selected based on its assumed three-year construction period. The importance of this sensitivity study is that the base FCR assumption is already favorably low for Case 0, and alternate financial parameter assumptions may result in an FCR that is higher than the base assumption. In this case, the COC will increase, and given the slope of the lines in Exhibit A-24, the resulting COC could be significantly higher than Case 0. Doubling the FCR would result in approximately a 52 percent increase in the COC.

As outlined in Section 8, alternate cases should be considered where financial parameters consistent with the chemical industry are selected, and a new FCR and COC can be calculated.

Exhibit A-24. COC sensitivity to fixed charge rate

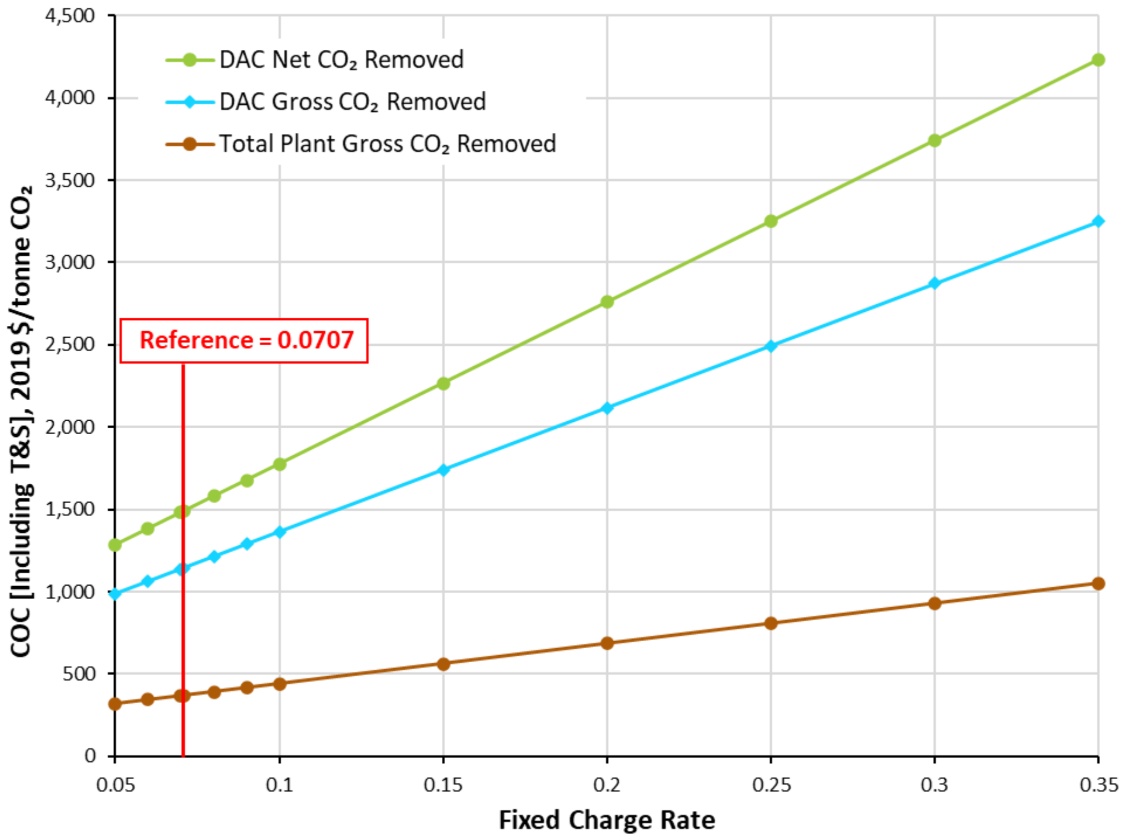


Exhibit A-25 shows the COC sensitivity to DAC system capture fraction for the three different bases of calculation. The reference Case 0 assumes that the DAC adsorbers remove 60 percent of the inlet CO_2 present in the air, and this value was selected based on the target capture rates presented in the literature. As expected, as the amount of CO_2 removed increases, and the denominator of the COC calculation increases, the total COC decreases. For perspective, at a capture rate of 30 percent, 904,270 tonnes/yr (996,786 tons/yr) of CO_2 must be captured from the combination of the DAC plant and Shell's Cansolv CO_2 capture system to achieve a net removal from the atmosphere of 100,000 tonnes/yr (110,230 tons/yr). As stated earlier, the reference Case 0 requires that a total of 402,530 tonnes/yr (443,713 tons/yr) be captured. At a capture rate of 90 percent by the DAC adsorbers, a total of only 292,160 tonnes/yr (322,051 tons/yr) must be removed to achieve the target net atmospheric removal. The COC calculated at 90 percent removal is $1,050/tonne CO_2 ($953/ton CO_2), a 29 percent reduction from Case 0.

Exhibit A-25. COC sensitivity to DAC system capture fraction

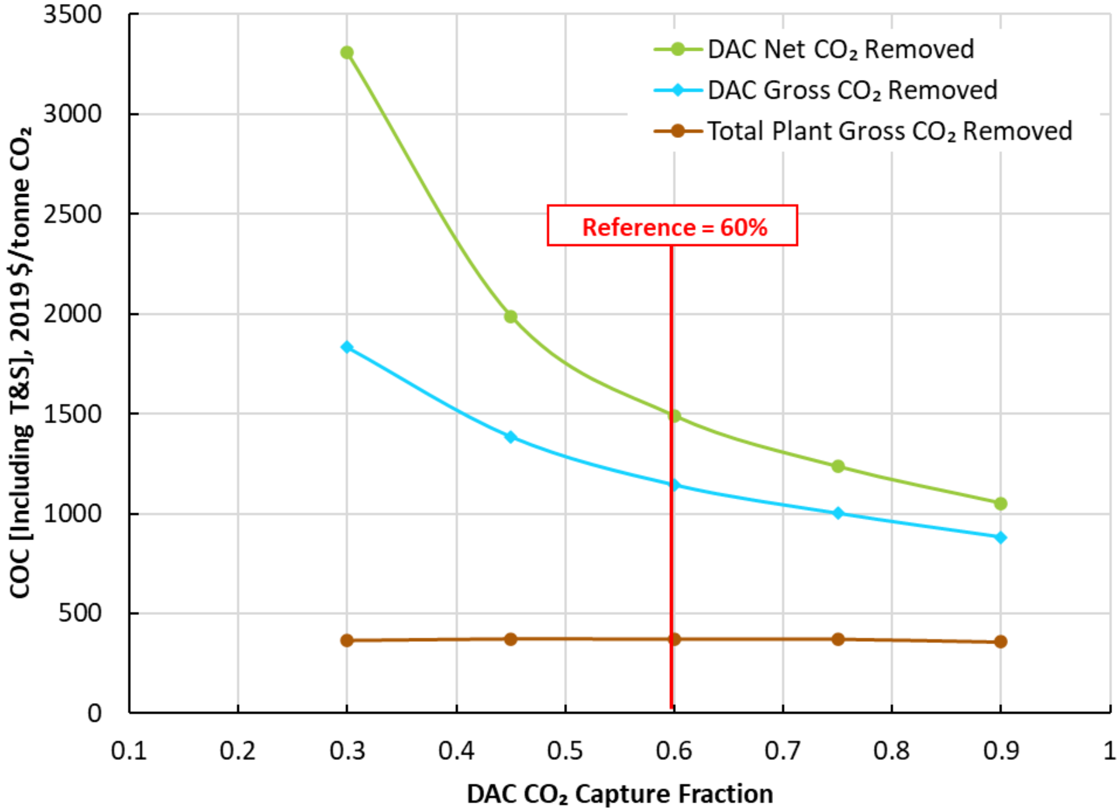


Exhibit A-26 shows the COC sensitivity to DAC sorbent regeneration energy for the three different bases of calculation. The reference Case 0 assumes a sorbent regeneration energy of 4.3 GJ/tonne CO_2 (1,847 Btu/lb CO_2), and this value was selected based on data presented in the literature for sorbent regeneration energy. As shown the COC result is not particularly sensitive to sorbent regeneration energy. A sensitivity range of +/-50 percent only results in a 1 percent increase or decrease in the COC.

Exhibit A-26. COC sensitivity to sorbent regeneration energy

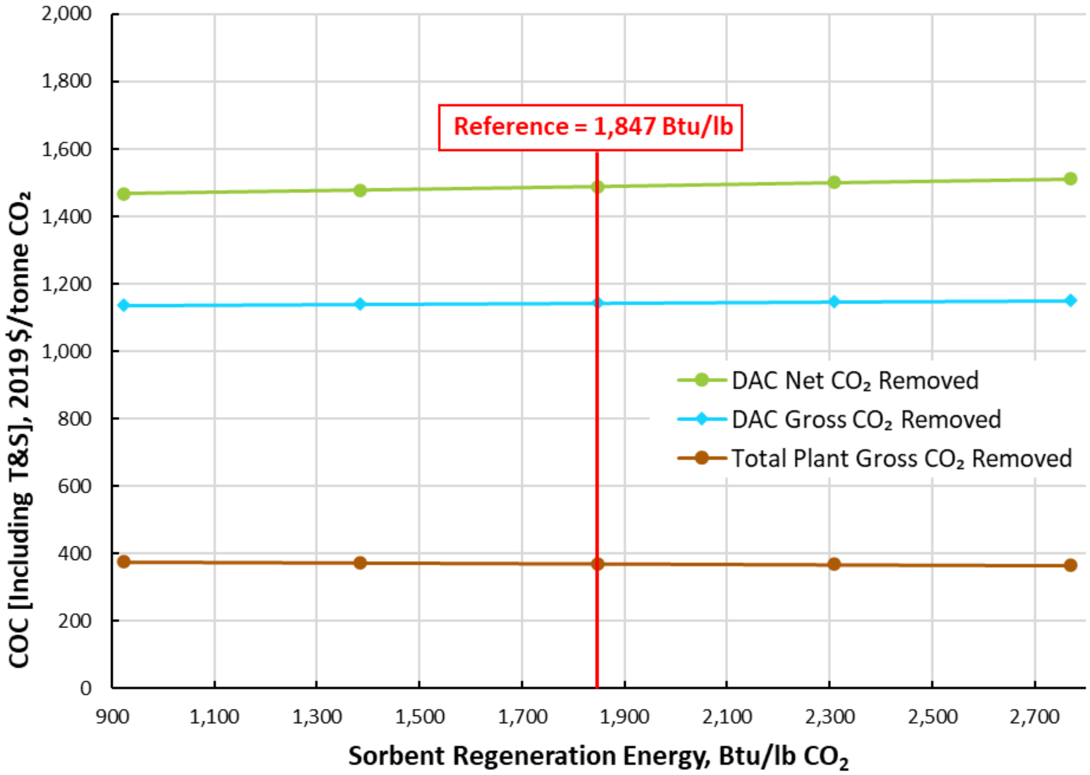
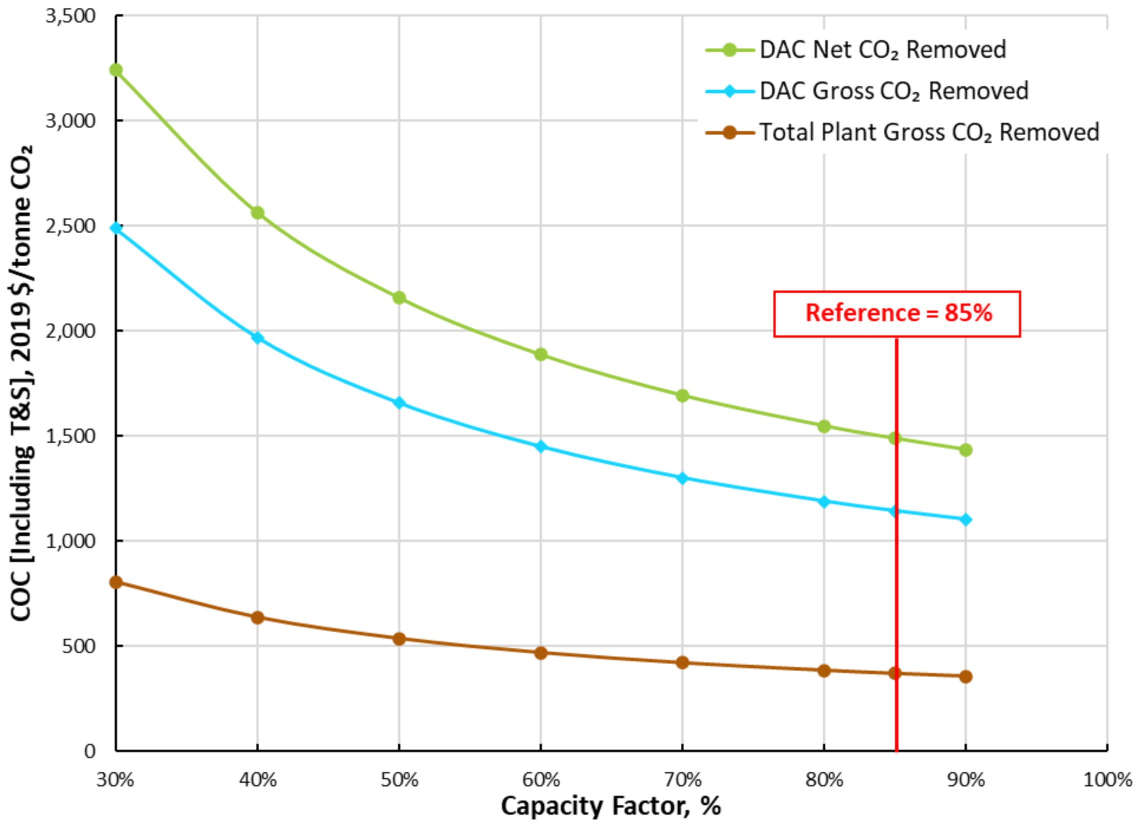


Exhibit A-27 shows the COC sensitivity to DAC system CF for the three different bases of calculation. The reference Case 0 assumes a CF of 85 percent. As expected, as the CF of the DAC plant reduces, the COC increases rapidly, indicating that high CFs will be required for a DAC plant to be economically competitive.

Exhibit A-27. COC sensitivity to CF



The reference Case 0 assumes that the spent DAC sorbent will be classified as a "non-hazardous waste" and can be disposed of offsite in a landfill at a disposal cost of $42/tonne ($38/ton). Exhibit A-28 presents a sensitivity case where the spent DAC sorbent is assumed to be classified as a "hazardous waste" that would carry a disposal cost of $88/tonne ($80/ton) and was applied at the reference 6 months sorbent life assumption. The hazardous and non-hazardous waste disposal costs were sourced from NETL's BBR4. [16] As shown in Exhibit A-28, the COC is relatively insensitive to disposal cost, with the hazardous waste classification increasing COC by only 2 percent.

Exhibit A-28. COC result for varying sorbent disposal cost

Component	COC DAC_{net}, $/tonne	COC DAC_{gross}, $/tonne	COC $Plant_{gross}$, $/tonne
Sorbent non-hazardous waste – Reference Case 0	1,488.9	1,143.0	369.9
Sorbent hazardous waste – Sensitivity Case	1,516.2	1,164.0	376.7
Percent increase in COC for hazardous waste designation	2%	2%	2%

The final sensitivity case considered examines the purity of the CO_2 product coming from the DAC adsorber during the desorption phase. The reference Case 0 assumes that the DAC CO_2 product is 100 percent pure CO_2 leaving the adsorber and entering the CO_2 compressor. There was limited information available in the literature regarding raw DAC product CO_2 purity leaving the adsorber vessels, with most references suggesting that the compressed CO_2 product leaving the DAC plant would be highly pure, or at a minimum, meet CO_2 pipeline specifications. Since the sorbent considered in this case study is represented as a generic sorbent, parameters such as void fraction represent unknowns. Therefore, it is difficult to determine how much residual air may be present in each adsorber when the system switches phases from adsorption to desorption, and how the air trapped in the void space, or how air components potentially adsorbed to the sorbent surface, would impact the final CO_2 product purity. Therefore, a single sensitivity case was considered where the DAC CO_2 compressor was removed and replaced with a cryogenic CO_2 purification and compression (CPU) unit.

The CPU data were sourced from a prior NETL report that examined advanced oxy-combustion technologies for coal-fired power plants. [30] Salient data for the CPU as presented in the reference is shown in Exhibit A-29. For perspective, the relevant Case 0 parameter values are also provided.

Exhibit A-29. Reference CPU data

Parameter	CPU Reference Value	DAC Case 0 Value
Inlet Flow Rate, lb/hr	1,221,161	38,568
Inlet CO_2 Purity, mol%	71.58	N/A
Inlet Pressure, psia	14.8	14.8
Inlet Temperature, °F	135	212
Outlet CO_2 Product Purity, mol%	99.99	-
Outlet Product Pressure, psig	2,200	-
Bare Erected Cost, x1000 2018$	242,814	-

As highlighted in Exhibit A-29, the reference CPU system processes ~31 times more inlet gas than the DAC Case 0 system requires to be treated. This difference in scale may introduce minor inconsistencies in the cost estimate results. The reference CPU system also purifies a stream with an inlet CO_2 concentration of 71.6 mole percent. Deviations from this value for the DAC system, which are presently unknown, may also introduce uncertainty in the sensitivity results presented.

Exhibit A-30 presents the relevant cost comparison data for Case 0 and the low-purity CO_2 sensitivity case, as well as the final COC result. Application of the CPU capital cost maintained the same process and project contingencies that were assumed in the reference report, and the same engineering home office and fee percentage that has been applied to the DAC system in this study.

Exhibit A-30. COC result for Case 0 (high-purity CO_2) versus a low-purity CO_2 case

Component	Case 0	Low-Purity CO_2 Case
DAC CO_2 Compressor and Aftercooler TPC, x1000 2019$	5,817	-
Scaled CPU TPC, x1000 2019$	-	23,408
Total Plant TOC, x1000 2019$	899,543	920,704
Total Plant TOC, $/tonne CO_2 net	8,995	9,207
COC DAC_{net}, $/tonne	1,489	1,512
Percent Increase in COC, %	-	1.6

Replacement of the DAC CO_2 compressor with the CPU adds an additional $17.6 M TPC to the sensitivity case capital cost. However, given the high capital cost of the reference Case 0, this value only represents approximately a 2 percent increase in the TPC, and results in a 1.6 percent increase in the COC.

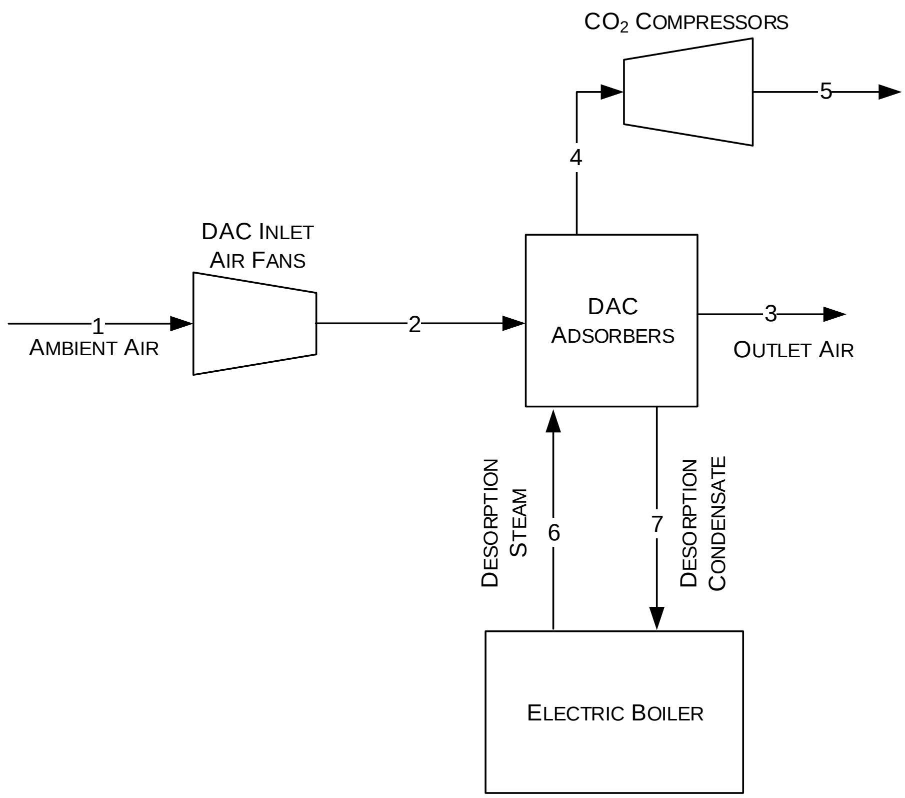
The CPU cost applied in this sensitivity study inherently assumes a fixed inlet CO_2 purity, and if the DAC process were to provide a CO_2 product stream below this purity, the CPU capital cost, and COC result, would increase.

APPENDIX B: CASE 0-EB – ELECTRIC BOILER

Case 0-EB considers the same direct air capture (DAC) system as Case 0, with the exception of the power and steam generation sub-systems. Case 0-EB utilizes an electric boiler to produce the steam needed for the thermal regeneration of the CO_2 adsorbent. It is assumed that the electricity required to satisfy the auxiliary load for the reference Case 0-EB is purchased at a sale price of $60/MWh. In order to gauge the impact of different renewable electricity sources, sensitivities were conducted on capacity factor (CF) and the price of purchased electricity. In this case, it is assumed that purchased electricity has no process-related CO_2 emissions, such that the gross capture rate of the DAC system, at 100,000 tonnes CO_2/yr (110,230 tons/yr), is equal to the net capture rate.

In this section, the Case 0-EB system is described. The system description follows the block flow diagram (BFD) in Exhibit B-1 and stream numbers reference the same exhibit. Exhibit B-2 provides process data for the numbered streams in the BFD. The DAC portion of the process considers 90 adsorber vessels and 45 air fans, but the flow rates in the stream table represent the total system.

Exhibit B-1. Case 0-EB BFD, sorbent-based DAC system



Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.

Exhibit B-2. Case 0-EB stream table, sorbent-based DAC system

	1	2	3	4	5	6	7
V-L Mole Fraction							
Ar	0.0092	0.0092	0.0092	0.0000	0.0000	0.0000	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0004	0.0004	0.0002	1.0000	1.0000	0.0000	0.0000
H_2O	0.0101	0.0101	0.0101	0.0000	0.0000	1.0000	1.0000
N_2	0.7724	0.7724	0.7726	0.0000	0.0000	0.0000	0.0000
O_2	0.2079	0.2079	0.2079	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg-mol/hr)	1,251,087	1,251,087	1,250,782	305	305	1,462	1,462
V-L Flowrate (kg/hr)	36,102,230	36,102,230	36,088,800	13,430	13,430	26,339	26,339
Solids Flowrate (kg/hr)	0	0	0	0	0	0	0
Temperature (°C)	15	21	21	100	30	153	138
Pressure (MPa, abs)	0.10	0.11	0.10	0.10	15.27	0.51	0.49
Steam Table Enthalpy (kJ/kg)[A]	30.65	36.60	36.62	86.50	-231.33	2,773.62	575.70
Aspen Plus Enthalpy (kJ/kg)[B]	-100.93	-94.98	-91.67	-8,875.57	-9,193.41	-13,197.72	-15,456.25
Density (kg/m³)	1.2	1.3	1.2	1.5	628.8	2.7	877.4
V-L Molecular Weight	28.857	28.857	28.853	44.010	44.010	18.015	18.015
V-L Flowrate (lb-mol/hr)	2,758,176	2,758,176	2,757,503	673	673	3,223	3,223
V-L Flowrate (lb/hr)	79,591,793	79,591,793	79,562,185	29,608	29,608	58,068	58,068
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0
Temperature (°F)	59	70	70	212	86	308	280
Pressure (psia)	14.7	15.5	14.8	14.8	2,214.7	73.5	70.6
Steam Table Enthalpy (Btu/lb)[A]	13.2	15.7	15.7	37.2	-99.5	1,192.4	247.5
Aspen Plus Enthalpy (Btu/lb)[B]	-43.4	-40.8	-39.4	-3,815.8	-3,952.5	-5,674.0	-6,645.0
Density (lb/ft³)	0.076	0.079	0.075	0.091	39.252	0.166	54.774

[A]Steam table reference conditions are 32.02°F & 0.089 psia
[B]Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

B.1 Case 0-EB – Process Description and Performance Results

Case 0-EB captures a net 100,000 tonnes CO_2/yr (110,230 tons/yr) from the atmosphere. Purchased power is required to satisfy plant auxiliary loads, and it is assumed that electricity is provided by renewable sources with negligible associated CO_2 emissions for a price of $60/MWh.

Ambient air (stream 1) is sent through fans and a duct system to distribute air to the 90 DAC adsorber vessels (stream 2). During steady-state operations, 81 of the 90 vessels will be operating in adsorption mode (90-hour cycle) and receiving air from the fans. The other 9 adsorption vessels will be in desorption mode (10-hour cycle) and utilize steam from the electric boiler (stream 6) to drive CO_2 from the sorbent. The electric boiler produces steam at 308°F

(153°C) and 73.5 psia. The product CO_2 is pulled from the adsorber vessels to the CO_2 compressor (stream 4), where it is compressed to 15.2 MPa (2,200 psig) (stream 5).

Overall plant performance is summarized in Exhibit B-3; Exhibit B-4 provides a detailed breakdown of the auxiliary power requirements.

Exhibit B-3. Case 0-EB plant performance summary

Performance Summary	
Total Gross Power, MWe	**0**
DAC Air Fans, kWe	59,690
DAC CO_2 Compression, kWe	1,490
Electric Boiler, kWe	19,510
Balance of Plant, kWe	188
Total Auxiliaries, MWe	**81**
Net Power, MWe	**-81**
DAC CO_2 Removed from Air (Gross), tonnes/yr	100,000
Net CO_2 Removed from Air, tonnes/yr	**100,000**

Exhibit B-4. Case 0-EB plant power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Circulating Water Pumps, kWe	70
Cooling Tower Fans, kWe	40
Feedwater Pumps, kWe	2
Ground Water Pumps, kWe	10
Miscellaneous Balance of Plant,[A] kWe	66
Air Fans, kWe	59,690
Electric Boiler, kWe	19,510
CO_2 Compression, kWe	1,490
Total Auxiliaries, MWe	**81**
Net Power, MWe	**-81**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

B.1.1 Environmental Performance

Case 0-EB utilizes an electric boiler for steam requirements and assumes renewable electricity is purchased to satisfy plant auxiliary load. Because the renewable electricity purchased by the plant is assumed to have negligible associated process emissions, this case reports no air emissions of SO_2, NOx, particulate matter (PM), Hg, CO, or CO_2.

The carbon balance for the plant is shown in Exhibit B-5. The carbon input to the plant consists of carbon in the air fed to the DAC adsorber vessels. Carbon leaves the plant as CO_2 through the DAC vessels and DAC CO_2 product stream.

Exhibit B-5. Case 0-EB carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
DAC Air (CO_2)	6,109 (13,468)	DAC CO_2	3,665 (8,081)
	–	DAC Vessel	2,444 (5,387)
Total	**6,109 (13,468)**	**Total**	**6,109 (13,468)**

Exhibit B-6 shows the overall water balance for Case 0-EB.

Exhibit B-6. Case 0-EB water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
Deaerator	–	–	–	0.0 (12)	0.0 (-12)
BFW Makeup	0.0 (13)	–	0.0 (13)	–	0.0 (13)
Cooling Tower	0.3 (73)	0.0 (1.0)	0.3 (72)	0.1 (16)	0.2 (55)
BFW Blowdown	–	0.0 (1.0)	0.0 (-1.0)	–	0.0 (-1.0)
Total	**0.3 (85)**	**0.0 (1.0)**	**0.3 (84)**	**0.1 (28)**	**0.2 (56)**

B.1.2 Energy Balance

An overall plant energy balance is provided in tabular form in Exhibit B-7.

Exhibit B-7. Case 0-EB overall energy balance (0 °C [32 °F] reference)

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
DAC Air	–	1,106 (1,049)	–	1,106 (1,049)
Raw Water Makeup	–	1.2 (1.1)	–	1.2 (1.1)
Auxiliary Power	–	–	291 (276)	291 (276)
TOTAL	0.0 (0.0)	1,108 (1,050)	291 (276)	1,399 (1,326)
Heat Out GJ/hr (MMBtu/hr)				
DAC Stack Gas	–	1,322 (1,253)	–	1,322 (1,253)
Motor Losses and Design Allowances	–	–	0.0 (0.0)	0.0 (0.0)
Cooling Tower Load[A]	–	36 (34)	–	36 (34)
Blowdown	–	0.0 (0.0)	–	0.0 (0.0)
DAC CO_2 Product Stream	–	-3.1 (-2.9)	–	-3.1 (-2.9)
Ambient Losses[B]	–	*0.4 (0.4)*	–	*0.4 (0.4)*
Power	–	–	0.0 (0.0)	0.0 (0.0)
TOTAL	–	1,355 (1,284)	0.0 (0.0)	1,355 (1,284)
Unaccounted Energy[C]	–	*44 (42)*	–	*44 (42)*

[A]Includes the CO_2 compressor and miscellaneous cooling loads
[B]Ambient losses include all losses to the environment through radiation, convection, etc.
[C]By difference

The cooling tower load includes the CO_2 compressor intercooler load and other miscellaneous cooling loads.

B.2 Case 0-EB – Cost Estimate Results

Exhibit B-8 shows a detailed breakdown of the capital costs; Exhibit B-9 shows the owner's costs, total overnight cost (TOC), and total as-spent capital (TASC); Exhibit B-10 shows the initial and annual O&M costs; and Exhibit B-11 shows the COC breakdown. Cost premiums that would be expected for first-of-a-kind technologies (e.g., various sorbent materials) are not reflected in the cost estimates. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required.

Exhibit B-8. Case 0-EB total plant cost details

Case:		DAC-0-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
	1					Sorbent Handling					
1.5	Sorbent Receive & Unload	$85	$0	$26	$0	$111	$22	$0	$20	$153	$2
1.6	Sorbent Stackout & Reclaim	$641	$0	$116	$0	$757	$151	$0	$136	$1,044	$10
1.7	Sorbent Conveyors	$957	$208	$231	$0	$1,396	$279	$0	$251	$1,927	$19
1.8	Other Sorbent Handling	$47	$11	$24	$0	$82	$16	$0	$15	$113	$1
1.9	Sorbent Handling Foundations	$0	$616	$812	$0	$1,427	$285	$0	$257	$1,969	$20
	Subtotal	$1,730	$835	$1,208	$0	$3,773	$755	$0	$679	$5,207	$52
	2					Sorbent Preparation and Feed					
2.5	Sorbent Preparation Equipment	$425	$18	$87	$0	$530	$106	$0	$95	$732	$7
2.6	Sorbent Storage & Feed	$712	$0	$269	$0	$981	$196	$0	$177	$1,353	$14
2.9	Sorbent Feed Foundation	$0	$286	$251	$0	$537	$107	$0	$97	$741	$7
	Subtotal	$1,137	$304	$607	$0	$2,048	$410	$0	$369	$2,826	$28
	3					Feedwater and Miscellaneous BOP Systems					
3.1	Feedwater System	$206	$353	$177	$0	$736	$147	$0	$132	$1,015	$10
3.2	Water Makeup & Pretreating	$283	$28	$160	$0	$472	$94	$0	$113	$679	$7
3.3	Other Feedwater Subsystems	$117	$38	$36	$0	$192	$38	$0	$35	$265	$3
3.4	Service Water Systems	$86	$164	$531	$0	$781	$156	$0	$187	$1,125	$11
3.5	Other Boiler Plant Systems	$46	$17	$42	$0	$104	$21	$0	$19	$144	$1
3.7	Waste Water Treatment Equipment	$535	$0	$328	$0	$864	$173	$0	$207	$1,243	$12
	Subtotal	$1,273	$601	$1,274	$0	$3,148	$630	$0	$694	$4,472	$45
	9					Cooling Water System					
9.1	Cooling Towers	$556	$0	$168	$0	$724	$145	$0	$130	$1,000	$10
9.2	Circulating Water Pumps	$77	$0	$5	$0	$81	$16	$0	$15	$112	$1
9.3	Circulating Water System Auxiliaries	$1,355	$0	$179	$0	$1,534	$307	$0	$276	$2,117	$21
9.4	Circulating Water Piping	$0	$256	$232	$0	$488	$98	$0	$88	$673	$7
9.5	Make-up Water System	$73	$0	$94	$0	$168	$34	$0	$30	$232	$2
9.6	Component Cooling Water System	$38	$0	$29	$0	$67	$13	$0	$12	$92	$1
9.7	Circulating Water System Foundations	$0	$59	$98	$0	$158	$32	$0	$38	$227	$2
	Subtotal	$2,099	$315	$805	$0	$3,220	$644	$0	$589	$4,453	$45
	10					Spent Sorbent Handling System					
10.6	Spent Sorbent Storage Silos	$473	$0	$1,448	$0	$1,922	$384	$0	$346	$2,652	$27

Case:		DAC-0-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
10.7	Spent Sorbent Transport & Feed Equipment	$1,610	$0	$1,596	$0	$3,206	$641	$0	$577	$4,425	$44
10.9	Spent Sorbent Foundation	$0	$330	$405	$0	$734	$147	$0	$176	$1,058	$11
	Subtotal	$2,084	$330	$3,449	$0	$5,863	$1,173	$0	$1,099	$8,135	$81
	11					Accessory Electric Plant					
11.1	Generator Equipment	$708	$0	$534	$0	$1,242	$248	$0	$224	$1,714	$17
11.2	Station Service Equipment	$1,750	$0	$150	$0	$1,900	$380	$0	$342	$2,622	$26
11.3	Switchgear & Motor Control	$2,499	$0	$434	$0	$2,932	$586	$0	$528	$4,046	$40
11.4	Conduit & Cable Tray	$0	$604	$1,740	$0	$2,344	$469	$0	$422	$3,235	$32
11.5	Wire & Cable	$0	$901	$1,611	$0	$2,513	$503	$0	$452	$3,467	$35
11.6	Protective Equipment	$42	$0	$147	$0	$190	$38	$0	$34	$262	$3
11.7	Standby Equipment	$228	$0	$210	$0	$438	$88	$0	$79	$604	$6
11.8	Main Power Transformers	$334	$0	$7	$0	$341	$68	$0	$61	$471	$5
11.9	Electrical Foundations	$0	$20	$51	$0	$72	$14	$0	$17	$103	$1
	Subtotal	$5,561	$1,525	$4,885	$0	$11,971	$2,394	$0	$2,159	$16,525	$165
	12					Instrumentation and Control					
12.4	Other Major Component Control Equipment	$469	$0	$299	$0	$767	$153	$38	$144	$1,103	$11
12.5	Signal Processing Equipment	$415	$0	$13	$0	$428	$86	$0	$77	$590	$6
12.6	Control Boards, Panels & Racks	$103	$0	$63	$0	$166	$33	$8	$31	$239	$2
12.7	Distributed Control System Equipment	$5,745	$0	$176	$0	$5,921	$1,184	$296	$1,110	$8,511	$85
12.8	Instrument Wiring & Tubing	$474	$379	$1,518	$0	$2,372	$474	$119	$445	$3,409	$34
12.9	Other Instrumentation & Controls Equipment	$329	$0	$761	$0	$1,089	$218	$54	$204	$1,566	$16
	Subtotal	$7,535	$379	$2,829	$0	$10,743	$2,149	$516	$2,011	$15,419	$154
	13					Improvements to Site					
13.1	Site Preparation	$0	$202	$4,294	$0	$4,497	$899	$0	$1,079	$6,475	$65
13.2	Site Improvements	$0	$650	$860	$0	$1,510	$302	$0	$362	$2,175	$22
13.3	Site Facilities	$624	$0	$655	$0	$1,279	$256	$0	$307	$1,842	$18
	Subtotal	$624	$853	$5,809	$0	$7,286	$1,457	$0	$1,749	$10,492	$105
	14					Buildings and Structures					
14.4	Administration Building	$0	$167	$113	$0	$280	$56	$0	$50	$386	$4
14.5	Circulation Water Pumphouse	$0	$3	$1	$0	$4	$1	$0	$1	$6	$0

Case:		DAC-0-EB	Sorbent DAC – Electric Boiler (Sensitivity)				Estimate Type:			Conceptual	
Plant Size (net tonnes CO_2/yr):		100,000					Cost Base:			September 2019	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/tonne (net)
14.6	Water Treatment Buildings	$0	$30	$28	$0	$58	$12	$0	$10	$80	$1
14.7	Machine Shop	$0	$244	$156	$0	$400	$80	$0	$72	$552	$6
14.8	Warehouse	$0	$199	$120	$0	$318	$64	$0	$57	$439	$4
14.9	Other Buildings & Structures	$0	$178	$129	$0	$307	$61	$0	$55	$424	$4
14.10	Waste Treating Building & Structures	$0	$334	$597	$0	$931	$186	$0	$168	$1,285	$13
	Subtotal	$0	$1,154	$1,143	$0	$2,297	$459	$0	$414	$3,170	$32
	15	Direct Air Capture System									
15.1	DAC Adsorption/Desorption Vessels	$0	$25,133	$20,564	$0	$45,697	$9,139	$4,570		$68,317	$683
15.2	DAC Carbon Dioxide (CO_2) Compression & Drying	$1,858	$279	$771	$0	$2,908	$582	$291	$567	$4,347	$43
15.3	DAC Carbon Dioxide (CO_2) Compressor Aftercooler	$69	$11	$30	$0	$110	$22	$0	$20	$152	$2
15.4	DAC System Air Handling Duct and Dampers	$5,874	$23,494	$9,789	$0	$39,157	$7,831	$3,916	$7,636	$58,540	$585
15.5	DAC System Air Handling Fans	$60,300	$0	$3,174	$0	$63,474	$12,695	$6,347	$12,377	$94,893	$949
15.6	DAC Desorption Process Gas Handling System	$152	$647	$212	$0	$1,011	$202	$101	$197	$1,511	$15
15.7	DAC Steam Distribution System	$260	$1,110	$364	$0	$1,734	$347	$173	$338	$2,592	$26
15.9	DAC System Controls Equipment	$394	$0	$251	$0	$646	$129	$65	$126	$966	$10
15.8	Electric Boiler	$2,554	$0	$134	$0	$2,688	$538	$0	$484	$3,709	$37
	Subtotal	**$71,460**	**$50,674**	**$35,289**	**$0**	**$157,424**	**$31,485**	**$15,463**	**$30,656**	**$235,027**	**$2,350**
	Total	**$93,504**	**$56,970**	**$57,299**	**$0**	**$207,773**	**$41,555**	**$15,978**	**$40,418**	**$305,724**	**$3,057**

Exhibit B-9. Case 0-EB owner's costs

Description	$/1,000	$/tonne
Pre-Production Costs		
6 Months All Labor	$3,370	$34
1-Month Maintenance Materials	$342	$3
1-Month Non-Fuel Consumables	$4,397	$44
1-Month Waste Disposal	$182	$2
25% of 1 Month's Fuel Cost at 100% CF	$0	$0
2% of TPC	$6,114	$61
Total	$14,406	$144
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$1,703	$17
0.5% of TPC (spare parts)	$1,529	$15
Total	$3,231	$32
Other Costs		
Initial Cost for Catalyst and Chemicals	$5,089	$51
Land	$125	$1
Other Owner's Costs	$45,859	$459
Financing Costs	$8,255	$83
Total Overnight Costs (TOC)	**$382,689**	**$3,827**
TASC Multiplier (IOU, 33 year)	1.093	
Total As-Spent Cost (TASC)	**$418,144**	**$4,181**

Exhibit B-10. Case 0-EB initial and annual operating and maintenance costs

Case:	DAC-0-EB	Sorbent DAC – Electric Boiler (Sensitivity)			Cost Base:	September 2019
Plant Size:	100,000	tonnes of CO_2 captured (net)			Capacity Factor (%):	85
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:		1.0
Operating Labor Burden:		30.00	**% of base**	Operator:		2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		2.0
				Lab Techs, etc.:		2.0
				Total:		**7.0**
Fixed Operating Costs						
					Annual Cost	
					($)	**($/tonne-net)**
Annual Operating Labor:					$3,069,066	$31
Maintenance Labor:					$2,323,505	$23
Administrative & Support Labor:					$1,348,143	$13
Property Taxes and Insurance:					$6,114,488	$61
Total:					**$12,855,202**	**$129**
Variable Operating Costs						
					($)	**($/tonne-net)**
Maintenance Material:					$3,485,258	$35
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	-	61	$1.90	$0	$35,836	$0
Makeup and Waste Water Treatment Chemicals (ton):	-	0.2	550	$0	$30,901	$0
Auxiliary Power (kWh):	-	1,941,069	$0.06	$0	$36,133,009	$361
DAC Sorbent (ft³):	1,272,344	6,972	$4.00	$5,089,376	$8,651,939	$87
Subtotal:				$5,089,376	$44,851,684	$449
Waste Disposal						
DAC Sorbent (ft³):	-	6,972	$0.86	$0	$1,860,167	$18.6
Subtotal:				**$0**	**$1,860,167**	**$18.6**
Variable Operating Costs Total:				**$5,089,376**	**$50,197,109**	**$502**
Fuel Cost						
Natural Gas (MMBtu):	0	0	$4.42	$0	$0	$0
Total:				**$0**	**$0**	**$0**

B.2.1 Cost Estimate Source

The capital cost estimates for Case 0-EB were developed by Black & Veatch and represent an AACE Class 5 estimate, with an uncertainty range of +/-50 percent. In all cases, this report relies on vendor cost estimates for component technologies and process equipment, corresponding to the assumption- and/or model-derived equipment specifications. It also applies process contingencies at the appropriate subsystem levels in an attempt to account for expected but undefined costs, which can be a challenge for emerging technologies. All major equipment components and features are based on commercially proven technology from reputable suppliers; no non-standard designs are required. All costs are reported in 2019 dollars.

Sorbent-based direct air capture (DAC) systems are an immature technology, lacking a history of commercial deployment at scale. The cost estimate methodology presented in this report is the same as that typically employed by NETL for mature plant designs and does not fully account for the unique cost premiums associated with the initial, complex integrations of established and emerging technologies in a commercial application. Thus, it is anticipated that initial deployments of plants based on the cases found in this report may incur costs higher the presented estimates. Absent demonstrated first-of-a-kind (FOAK) plant costs associated with a specific plant configuration/technology, it is difficult to explicitly project fully mature, N^{th}-of-a-kind (NOAK) values. Consequently, the cost estimates provided herein represent neither FOAK nor NOAK costs. Nevertheless, the application of a consistent methodology - and the presentation of detailed equipment specifications and costs based on contemporary sources - facilitate comparison between cases as well as sensitivity analyses to guide R&D, and generally improve upon many publicly available estimates characterized by more opaque methods and sources, and less detail.

Anticipated actual costs for projects based upon any of the cases presented herein 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 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.

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 here.

B.2.2 Cost of CO_2 Capture Results

Using the methodology presented in Section 3.6, Exhibit B-11 presents the results for the COC for Case 0-EB.

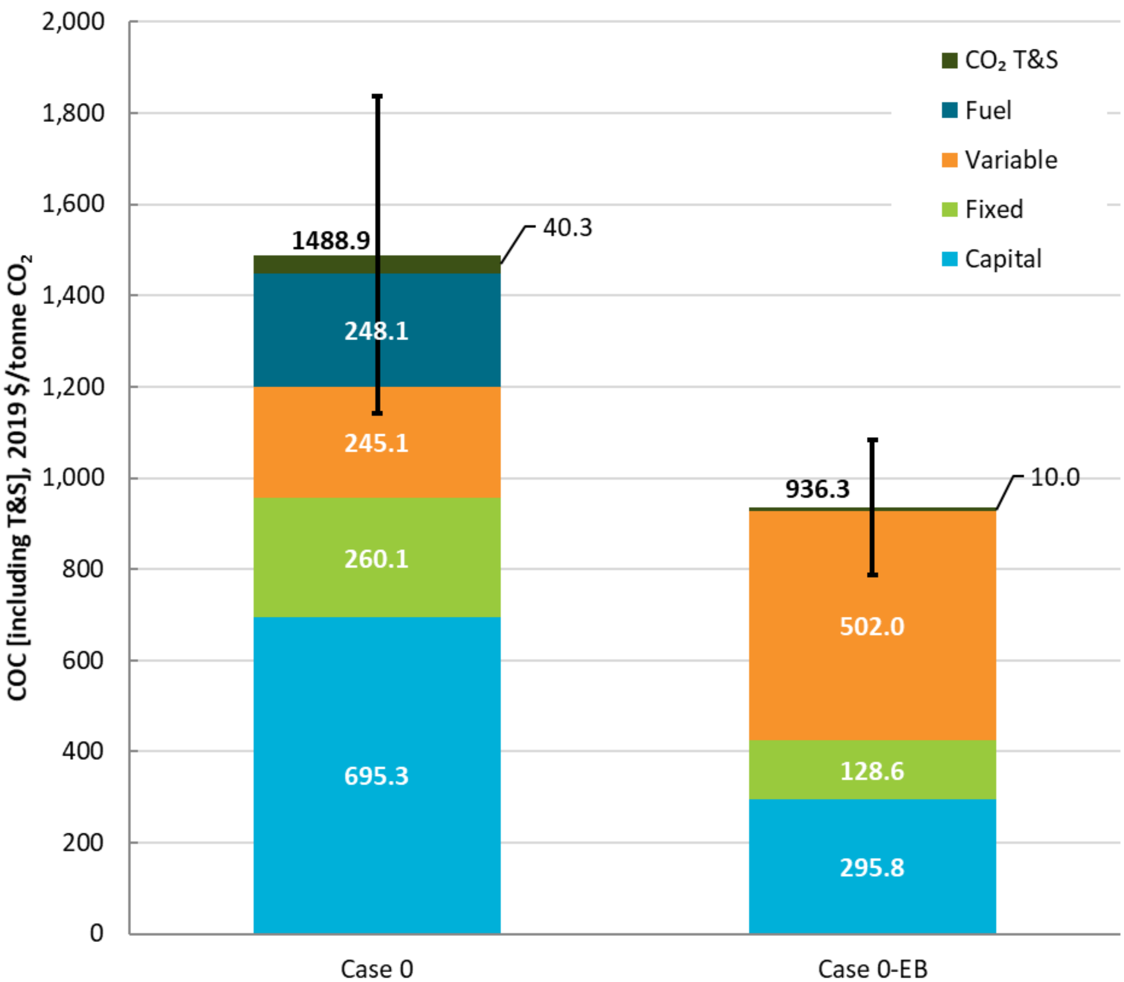
Exhibit B-11. Case 0-EB COC

Component	COC DAC_{net}, $/tonne
Capital	295.8
Fixed	128.6
Variable	502.0
Fuel	0.0
Total (Excluding T&S)	**926.3**
CO_2 T&S	10.0
Total (Including T&S)	**936.3**

For the COC DAC_{net} result of \$936/tonnes CO_2 (\$849/tons CO_2) (including T&S), a total CO_2 flow of 100,000 tonnes/yr (110,230 tons CO_2/yr) is used. In Case 0-EB, auxiliary load requirements are fulfilled by renewable electricity; for simplicity, it is assumed that the renewable electricity source produces power with no process-related CO_2 emissions. Therefore, in Case 0-EB, the net capture rate is equivalent to the gross capture rate.

Exhibit B-12 presents the COC results graphically and includes error bars relating to the uncertainty in the capital cost estimate. The COC result of Case 0 is also included for comparison. As highlighted previously, the capital estimates represent AACE Class 5 estimates, with an uncertainty range of +/-50 percent. The COC ranges presented are not reflective of other changes, such as variation in fuel price, labor price, CF, or other factors.

Exhibit B-12. Case 0 and Case 0-EB COC plot and uncertainty ranges



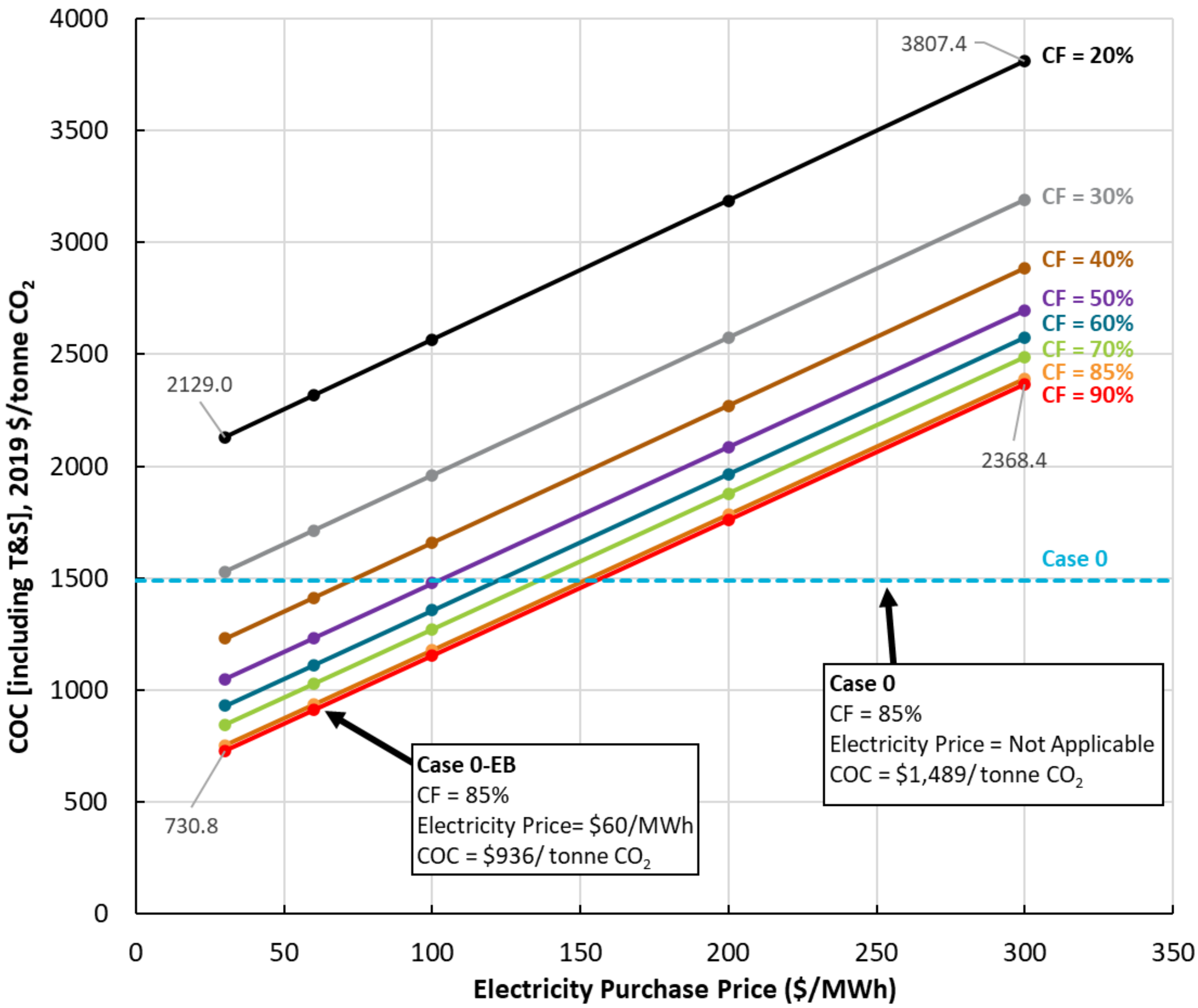
Note: Case 0-EB assumes that the auxiliary load is satisfied by purchased electricity at a price of \$60/MWh. Additionally, for purposes of sizing the plant, it assumes that the purchased electricity has no associated process CO_2 emissions

B.2.3 Sensitivity Analysis

In Case 0-EB, it is assumed that all electricity requirements are fulfilled by renewable sources with no associated CO_2 emissions. Because the selling price and CF of renewable electricity may vary depending on generation technology type, region, inclusion of energy storage, and other factors, a sensitivity analysis was conducted over a range of electricity purchase prices and CFs.

Exhibit B-13 shows the net COC sensitivity to electricity purchase price for several different assumed CFs. Electricity prices ranging $30–300/MWh and CFs ranging 20–90 percent were considered. Over this range of electricity prices and CFs, the COC ranges $731–3,807/tonnes CO_2. At CFs of 30 percent and lower, the COC range is above the COC result for Case 0 even at the lowest electricity price assumed ($30/MWh). At a CF of 40 percent, the price of purchased electricity must be less than $72/MWh in order to achieve a COC lower than Case 0. At 90 percent CF, the price of purchased electricity must be less than $159/MWh in order to achieve a COC lower than Case 0.

Exhibit B-13. Case 0-EB COC sensitivity to electricity purchase price and CF



Note: The system energy requirements (both electric and thermal) in Case 0-EB and Case 0-EB sensitivities are satisfied by electricity purchase (thermal requirements satisfied by an electric boiler). The Case 0 COC is presented for comparison with

Case 0-EB and Case 0-EB sensitivity results. The system energy requirements (both electric and thermal) in Case 0 are provided by an NGCC with 90% CO_2 capture. To account for process CO_2 emissions, the gross DAC capacity in Case 0 is upsized by 30% compared to the gross capture capacity of Case 0-EB.

When considering the potential variability of renewable sources without sufficient energy storage to smooth out disruptions in supply, and the potential increase in levelized cost of electricity (LCOE) for renewables sources paired with sufficient energy storage, the base result presented in Section B.2.2 for Case 0-EB is viewed as overly optimistic. While low and negative LCOEs have been highlighted in the literature as a result of excess renewable generation during periods of low demand and high renewable availability, [31] it is unrealistic to assume that these low LCOE values would be available to the DAC plant for large portions of a single day. Therefore, from the perspective of impact of CF and LCOE on the COC result for the Case 0-EB configuration considered, there is little opportunity to reduce the COC beyond the Case 0-EB result shown by only considering these two parameters. Other parameters, such as assumed system pressure drop, will be more impactful. If system pressure drop were able to be reduced, the electrical auxiliary load of Case 0-EB would reduce, and all the lines in Exhibit B-13 would shift down. However, applying this same system pressure drop reduction to Case 0 would also shift the Case 0 COC result down. Thus, it is assumed that the relative comparison of Case 0 and Case 0-EB COC results would remain largely the same, but that the absolute results compared with other sources of CO_2 may become more favorable for these DAC configurations.

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