NATIONAL ENERGY TECHNOLOGY LABORATORY

# USER GUIDE FOR THE PUBLIC INDUSTRIAL $CO_2$ CAPTURE RETROFIT DATABASE MODELS

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## Disclaimer

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AFB | Atmospheric fluidized bed |
| AGR | Acid gas removal |
| BOP | Balance of plant |
| Btu | British thermal unit |
| CCF | Capital charge factor |
| CCRD | Carbon capture retrofit database |
| CCS | Carbon capture and storage |
| CEPCI | Chemical Engineering Plant Cost Index |
| CF | Capacity factor |
| $CO_2$ | Carbon dioxide |
| COP | Cost of product |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| FLIGHT | Facility Level Information on GreenHouse gases Tool |
| GHG | Greenhouse gas |
| hr | Hour |
| ID | Identification |
| IND | Industrial |
| ISO | International Organization for Standardization |
| kW | Kilowatt |
| kWh | Kilowatt hour |
| LP | Low pressure |
| MATS | Mercury and Air Toxic Standards |
| MMBtu | Million British thermal unit |
| MW | Megawatt |
| MWh | Megawatt hour |
| N/A | Not applicable |
| NETL | National Energy Technology Laboratory |
| NGCC | Natural gas combined cycle |
| NOx | Oxides of nitrogen |
| NSPS | New Source Performance Standards |
| O&M | Operating and maintenance |
| PC | Pulverized coal |
| QGESS | Quality Guidelines for Energy System Studies |
| $SO_2$ | Sulfur dioxide |
| T&S | Transport and storage |
| TOC | Total overnight cost |
| tonne | Metric ton |
| TPC | Total plant cost |
| TPD | Tons per day |
| TPY | Tons per year |
| U.S. | United States |
| yr | Year |

# 1 INTRODUCTION

The United States (U.S.) Department of Energy's (DOE) National Energy Technology Laboratory (NETL) produced three carbon capture retrofit databases (CCRDs) that contain a collection of units selected from power generation and industrial sources (IND) sectors located in the United States that are either operating or on standby. The power generation category is subdivided into the pulverized coal (PC) CCRD—containing coal-fired and atmospheric fluidized bed (AFB) units—and the natural gas combined cycle (NGCC) CCRD—containing natural gas-fired combined cycle and combined cycle single shaft units. The IND CCRD contains facilities from the ammonia, cement, ethanol, refinery-produced hydrogen, and natural gas processing industries.

Plant data for the IND CCRD are sourced from the Environmental Protection Agency's (EPA) greenhouse gas (GHG) reporting program, EPA's Facility Level Information on GreenHouse gases Tool (FLIGHT), and the EPA's GHG Envirofacts GHG Query Tool (used for acid gas removal (AGR) emissions). [1, 2, 3]

The CCRDs provide high-level analyses on the incremental costs for retrofitting point sources with carbon dioxide ($CO_2$) capture and/or compression systems.

The technologies used for $CO_2$ capture in the CCRDs are based on $CO_2$ capture systems as presented in the Industrial Capture reports. [4, 5] The default capture rates for the technologies are the assumed design rates based on the $CO_2$ fed to the capture system. For user-specified inputs that differ from the default, it is assumed that a bypass is installed such that the design capture rate of the system remains at the default value for the technology. The results are based on scaling cost and performance data and may not accurately reflect a direct vendor quote for any system modeled in the CCRDs.

This document is intended to provide a general guide to the IND CCRD. Efforts have been made to ensure similarities between each of the CCRDs. However, as the sources of $CO_2$ vary, differences will exist—most notably in the IND CCRD.

# 2 Accuracy of Results

The cost and performance results presented in the CCRDs are based on assumptions necessitated by limitations of available data. These inaccuracies compound those of the reference cost and performance data[a] used as the basis for developing the reported results. The methodology used to develop the cost and performance results reported in each CCRD can be found in the Appendix: Industrial Sources Database Calculations.

## 2.1 General Factors

The reference costs for all CCRDs are predicated on baseload operation, so no cost or performance considerations are made for turn-down capability. In general, it is expected that designing a system with turn-down capabilities will result in additional costs and operating a system below its nameplate capacity will result in efficiency penalties, compared to baseload operation.

Additionally, scaling cost and performance data to units of significantly differing sizes, compared to the reference data, will introduce inaccuracies due to the nature of process design. For instance, step-wise changes in cost and performance will not be captured by this scaling method.

The capital charge factors for use in calculating the cost of product are based on recommended financial structures used in the industrial report via a simplified equation that is described in the Quality Guidelines for Energy System Studies (QGESS) document "Cost Estimation Methodology for NETL Assessments of Power Plant Performance," which provides the typical assumptions used in greenfield calculations. [5, 6] Several factors influence the capital charge factors including the interest rate, the required return on equity, the economic life of the plant, and the percentage of debt and equity.

The 150 percent declining balance method with half-year convention percentages was used to calculate depreciation. [7] As the typical greenfield plant is specified with a 30-year plant life and a depreciation recovery period of 20 years, [6] it was assumed that plants with a 20- and 10-year life would have a depreciation recovery period of 15 and 7 years, respectively.

For units that require multiple trains of $CO_2$ capture and compression, the calculations assume an even distribution of flue gas flow to all trains with each train being of identical design. By increasing the number of trains and decreasing the average size, increased costs are incurred due to the economy of scale. These additional costs may be avoided if a vendor is capable of offering an alternative design that can handle a flow rate that exceeds the estimated maximum of the reference plant. Optimization options may also be available but are not considered in the CCRDs. For instance, one unit at maximum capacity may be utilized with an additional unit of a different capacity to handle the excess load.

Furthermore, all reference systems are designed for International Organization for Standardization (ISO) ambient conditions, [8, 5] and no cost or performance adjustments are

[a] The accuracy of the reference cost data is considered to be -15%/+30%. [6]

made to account for the operating ambient conditions. As the reference plants are not designed for seasonal variations in ambient conditions, the capital cost and auxiliary load may be under-estimated for systems sensitive to the ambient conditions, such as the cooling system, and all related systems, such as the intercooled $CO_2$ compressors.

The accuracy of the cooling tower cost and performance is dependent on the accuracy of the $CO_2$ capture and compression system's performance results (discussed below), as the additional cooling tower capacity is based on the cooling water requirement of these systems.

A single retrofit factor is applied to all sites with no consideration given to the amount of retrofit equipment required, the available space, or other site-specific conditions. As the plant configuration has a significant impact on the actual installation costs and design (and therefore equipment costs) of each system, the site-specific retrofit factor would be expected to deviate significantly from the average value entered in the user input tab.

Lastly, the designation of a region as being either dry or wet (for use in the cooling system selection) is determined on a region wide basis. Therefore, variations within the region are not accounted for and may not accurately represent the cooling system that would be installed.

## 2.2 Industrial Sources Database

In the IND CCRD, the rate of $CO_2$ emissions is reported for all facilities and no considerations are given for any oxides of nitrogen (NOx), sulfur dioxide ($SO_2$), or other emissions control equipment. Regardless, many similarities to the PC and NGCC CCRD exist between the factors that affect the expected accuracy of the results in the IND CCRD. Therefore, this section focuses on the differences and the unique factors that affect the accuracy of the IND CCRD's results.

The equipment associated with the $CO_2$ capture system varies by process, and an equipment list is provided in Exhibit 2-1.

***Exhibit 2-1. $CO_2$ capture system equipment list, by process***

<table>
<tr><th>Process</th><th>Capture/ Purification</th><th>Low Pressure Steam Boiler</th><th>Pre-Cooler</th><th>$CO_2$ Compressors</th><th>After-Cooler</th><th>Cooling Water System</th></tr>
<tr><td>Ammonia Primary Reformer[A]</td><td>x</td><td>x</td><td>x</td><td rowspan="2">x</td><td rowspan="2">x</td><td rowspan="2">x</td></tr>
<tr><td>Ammonia Stripper[B]</td><td></td><td></td><td></td></tr>
<tr><td>Cement[A]</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Ethanol</td><td></td><td></td><td>x</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Hydrogen[A]</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Natural Gas</td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
</table>

[A] The exhaust gas from the natural gas-fired low-pressure (LP) steam boiler is combined with the process $CO_2$ product stream prior to the capture system if the user selects the option to include natural gas boiler emissions in the capture feed.
[B] The vent stream from the ammonia stripper is combined with the ammonia primary reformer $CO_2$ product stream prior to the pre-cooler.

For processes that utilize Shell's $CO_2$ capture systems, the cost and performance of the system is impacted in an identical way as the solvent-based $CO_2$ capture system for PC and NGCC power generation systems. Namely by variances in composition, dilution, purity, and operating conditions. However, no cost or performance adjustments are made to account for these variations.

For the remaining processes, only cooling and compression is utilized (the natural gas process does not require pre-cooling as the feed stream is at a sufficiently low temperature). As such, the only impact the purity of the feed stream will have on the cost and performance of the system will be due to the increased flow rate (larger compressors and higher auxiliary load). However, the calculations assume that the feed stream is at an identical purity to the reference cases and that no purification is required within the compression system.

Variations in operating pressure in the processes utilizing only cooling and compression can have an appreciable impact on the capital cost and auxiliary load of the $CO_2$ compressors while variations in operating temperature will impact the pre-cooler (or first stage of compression if no pre-cooler is present) and subsequently the cooling tower. However, as with the other CCRDs, no cost or performance adjustments are made to account for variations in process operating conditions.

The Cement and Natural Gas processes utilize an integrally-geared centrifugal $CO_2$ compressor (identical to the PC and NGCC CCRDs) and the Hydrogen process utilizes a centrifugal $CO_2$ compressor with two inlets, whereas the remaining processes utilize a reciprocating type (utilized for small feed rates). No cost or performance adjustments were made for plants that operate at $CO_2$ production rates outside the recommended operating range of these systems.

For processes that utilize Shell's $CO_2$ capture systems, a natural gas boiler is included to produce the required steam for the capture system. There is an option for the flue gas from this boiler to be added to the $CO_2$ capture system feed with no additional treatment. It is assumed that this stream is of insufficient size to substantially affect the purity of the mixed stream and that no additional processing is required. However, it does have the potential to have an appreciable impact on the size and auxiliary load for the inlet induced draft fan of the capture system.

Lastly, it was assumed that no by-products were co-produced by any of the processes. However, a significant portion of the $CO_2$ produced by the facilities could potentially be diverted for this purpose. For instance, urea co-production has been noted to be practiced at several ammonia process plants, which would ultimately change the amount of $CO_2$ emitted per tonne ammonia produced. [5]

# 3 Industrial Sources Database

This section provides a high-level guide for the IND CCRD. The sub-sections discuss the process of starting, saving, and closing the CCRD; layout; input options; and results (summary table and charts). Calculations are discussed in the Appendix: Industrial Sources Database Calculations.

## 3.1 Starting, Saving, and Closing

The IND CCRD opens to a disclaimer tab that provides a notification that macros must be enabled for the CCRD to operate. A link to a copy (a PDF file) of the User Guide is also provided. Upon pressing the "Start Program" button (with macros enabled), a message is displayed asking for acknowledgement that Section 2 of the User Guide has been read. If "No" is pressed, a copy of the User Guide is opened and a prompt to read Section 2 before continuing is displayed. If "Yes" is pressed, the layout described in the following section is presented.

If the CCRD is saved at any point (other than when closing), the following message is displayed: "Warning: If you save now, any future changes will automatically be saved upon exiting."

When closing, either the message "Workbook will be saved" is displayed, if the CCRD was previously saved, or the option to save or close without saving will be presented. Before the CCRD is closed, if the CCRD was saved at any point, the disclaimer tab remains visible but all other tabs are hidden.

## 3.2 Layout

Upon pressing the "Start Program" button (with macros enabled) and acknowledging that Section 2 of the User Guide has been read, the CCRDs will make the following tabs visible:

1. User Input
2. Summary
3. Charts
4. Results
    a. Ammonia
    b. Cement
    c. Ethanol
    d. Hydrogen
    e. Natural Gas
5. Revision Log

Tabs 1 through 3 are discussed in more detail in subsequent sections. The Results tabs are discussed as they relate to other tabs in their respective sections. The Revision Log maintains a list of major changes made to the CCRD from the previous version.

In addition to the visible tabs, the following tabs are also present in the IND CCRD, but are hidden by default:

1. Cost Parameters
2. Calculations
    a. Ammonia
    b. Cement
    c. Ethanol
    d. Hydrogen
    e. Natural Gas
3. Purchased Power Cost
4. EPA GHG Data
5. EPA FLIGHT Data
6. EPA AGR Data
7. CostIndices
8. Water Availability

The Cost Parameters tab stores the data for the default values shown in the User Input tab, as well as the reference cost and performance values used within the Calculations tabs, along with their associated citations and notes.

The Calculations tabs contain facility identification and pre-retrofit $CO_2$ emissions data, along with all calculations and results used throughout the CCRD. This tab sources its data from the Cost Parameters tab and tabs 3 through 6, which serve as data lookup tables.

## 3.3 User Input

The parameter selection for all five of the industrial processes in the IND CCRD can be specified in the User Input tab simultaneously. Exhibit 3-1 provides a list of the basic input parameters available, while Exhibit 3-2 provides a list of the advanced parameters. There are multiple options available for each of the parameters, including a user input option where the value to be used in the calculations may be defined. A macro is activated when the default options are selected that over-writes the contents of the associated parameter value cell.

***Exhibit 3-1. Basic user input parameters for the IND CCRD***

| Parameter | Units | Value | | | | |
|---|---|---|---|---|---|---|
| | | Ammonia | Cement | Ethanol | Hydrogen | Natural Gas |
| $CO_2$ Capture Rate (Source 1) | Choose Option | Default | Default | Default | Default | Default |
| | % | 100% | 90% | 100% | 99% | 100% |
| $CO_2$ Capture Rate (Source 2) | Choose Option | Default | N/A | N/A | N/A | N/A |
| | % | 90% | N/A | N/A | N/A | N/A |
| Capacity Factor | Choose Option | Default | Default | Default | Default | Default |
| | % | 84% | 79% | 84% | 97% | 61% |
| Minimum Retrofit Unit Capacity Applicability Limit | Choose Option | Default | Default | Default | Default | Default |
| | TPD-$CO_2$ | 0 | 0 | 0 | 0 | 0 |
| Retrofit Cost Factor | Choose Option | Default | Default | Default | Default | Default |
| | | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 |
| Capital Charge Factor | Choose Option | Default | Default | Default | Default | Default |
| | Choose Option | 30-Year | 30-Year | 30-Year | 30-Year | 30-Year |
| | | 0.055 | 0.054 | 0.070 | 0.046 | 0.060 |

Note: The names of the industrial processes (Ammonia, Cement, etc.) can be edited if desired.

$CO_2$ Capture rate refers to the percent of the $CO_2$ in the feed to the capture system that is captured. $CO_2$ Capture rate (source 1) is the primary parameter and applicable to all industries. $CO_2$ Capture rate (source 2) is only applicable to the ammonia facilities primary reformer.

The **$CO_2$ capture rate**[b] can be set to either 1) default or 2) user input. For processes with a default capture rate of 100 percent (ammonia stripper vent, ethanol, and natural gas,) the existing source of emissions is nearly pure [5]; therefore, only cooling and compression are required. Ammonia secondary capture (from the primary reformer) and cement processes that capture 90% (by default) use Shell's Cansolv $CO_2$ capture system. [5] Refinery hydrogen processes that capture 99% (by default) use Shell's ADIP-Ultra amine-based pre-combustion $CO_2$ capture system. [5]

The **capacity factor** can be set to either 1) default—which is set based on the 2021 average industry utilization [9], [10], [11], [12], [13] or 2) user input.

The **retrofit unit capacity applicability limit** can be set to either 1) default—which is 0 TPD-$CO_2$[c]; 2) 25 MW equivalent—which is set to 534 TPD-$CO_2$ and represents the theoretical equivalent $CO_2$ production rate of the Fossil Energy Baseline's Case B11A [8], scaled down to 25

[b] Only the ammonia process has a second source, as it represents a modification to the reference ammonia process configuration described in "Cost of Capturing $CO_2$ from Industrial Sources – Revision 2." [5] The first source is from the ammonia stripper vent, whereas the second source is from the primary reformer flue gas.

[c] The default was set to 0 TPD-$CO_2$ as there are currently no regulations controlling $CO_2$ emissions from industrial processes. Therefore, this is considered an elective selection based on economic viability, which will not have a standard minimum.

MW; or 3) user input. All facilities with a production rate below the retrofit unit capacity applicability limit are excluded from the calculations.

The **retrofit cost factor** can be set to either 1) default or 2) user input. This factor is intended to be used to adjust the capital costs of the facility, specifically the total plant cost (TPC), to reflect the increased capital expenditure incurred due to the added difficulty of retrofitting an existing facility, relative to the cost of constructing a $CO_2$ capture system at a greenfield facility—for which the reference costs used in the IND CCRD were developed.

The **capital charge factor** (CCF) can be set to either 1) default or 2) user input. Ammonia Stripper Vent, Ethanol, and Natural Gas facilities are considered high-purity sources and their CCF default values are for a 1-year construction period. Ammonia Primary Reformer, Cement, and Hydrogen facilities are considered low-purity sources and their default CCF values are for a 3-year construction period. The CCF values used for ammonia in the calculations reflect the weighted average of the vent and primary reformer capture system capital components. The default values are based on assumptions in the Industrial Sources report and equations in the updated cost estimating QGESS. [5, 6]. The CCF can be further defined as having either a 10-, 20-, or 30-year economic life and are based on the CCFs reported in the Industrial Sources. [5]

***Exhibit 3-2. Advanced user input parameters for the IND CCRD***

| Parameter | Units | Value | | | | |
|---|---|---|---|---|---|---|
| | | Ammonia | Cement | Ethanol | Hydrogen | Natural Gas |
| Maximum $CO_2$ Capture Rate Per Train | Choose Option | Default | Default | Default | Default | Default |
| | TPD | 21,867 | 27,430 | 122,453 | 54,516 | 121,229 |
| Cost Year Basis | Choose Option | Default | Default | Default | Default | Default |
| | Year | 2018 | 2018 | 2018 | 2018 | 2018 |
| Cooling Preference | Choose Option | State | State | State | State | State |
| Purchased Electricity Price | Choose Option | State | State | State | State | State |
| | $/MWh | Varies | Varies | Varies | Varies | Varies |
| Purchased Natural Gas Price | Choose Option | State | State | N/A | State | N/A |
| | $/MMBtu | Varies | Varies | N/A | Varies | N/A |
| Additional Auxiliary Load Penalty | Choose Option | None | None | None | None | None |
| | kW/TPD-$CO_2$ | N/A | N/A | N/A | N/A | N/A |
| $CO_2$ Transport and Storage Costs | Choose Option | None | None | None | None | None |
| | $/tonne captured | N/A | N/A | N/A | N/A | N/A |

The **maximum $CO_2$ capture rate per train** can be set to either 1) default or 2) user input. If a facility has a $CO_2$ production rate greater than the maximum per train, multiple trains will be used ($CO_2$ flow will be divided evenly across trains). If the user input option is selected, the maximum capture rate can be specified; however, a macro will reset the cell to the default value if a capture rate that is higher than the default is entered and a notification will be displayed.[d]

The **cost year basis** can be set to either 1) default or 2) 2021. By default, the results presented in the CCRD are provided on a 2018-year dollar basis. The calculations use data from the Chemical Engineering Plant Cost Index (CEPCI) [14] to scale the results to a 2021-year dollar basis. Alternative years can be used by changing the year and index formulas on the CostIndices tab.

The **cooling preference**[e] can be set to either 1) wet—adds a wet cooling system, 2) dry—adds a dry cooling system, or 3) state—which selects the type of cooling system added based on the state designation as listed in the hidden “Water Availability” tab.[f] The cooling system is added to compensate for the increased cooling for the $CO_2$ capture system, where applicable.

The **purchased electricity price** can be set to 1) Default—which is $60/MWh based on the updated Industrial Sources report [5], 2) state—which uses the state annual weighted average retail sales of electricity to ultimate customers’ price for industrial sectors as listed in the hidden “Purchased Power Cost” tab [15], or 3) user input. This parameter is the cost to purchase additional electricity for the auxiliary load requirements of the equipment and balance of plant demands associated with the retrofit.

The **purchased natural gas price** can be set to 1) Default—which $4.42/MMBtu based on the updated Industrial Sources report [5], 2) state—which uses the state annual average price of natural gas delivered to consumers as listed in the hidden “Purchased Power Cost” tab [16], or 3) user input. This parameter is the cost to purchase natural gas for the steam boiler used by the $CO_2$ capture system. This option is shown as “N/A” for process that only require cooling and compression (no capture unit).

The **additional auxiliary load penalty** can be set to either 1) none or 2) user input. This parameter is intended to be used as an adjustment for known additional equipment or considerations that would be required for a capture system that are not included in the current version of the CCRD.

The **$CO_2$ transport and storage costs** can be set to either 1) none, 2) default—currently $10/tonne $CO_2$ [4], or 3) user input.

## 3.4 RESULTS

Based on the selections specified in the User Input (discussed in Section 3.3), results are calculated (discussed in the Appendix: Industrial Sources Database Calculations) and presented in several forms. All the results of the individual facilities can be accessed in their respective

[d] The default maximum $CO_2$ capture rate per train is based on the value used in the PC CCRD and scaled based on $CO_2$ concentration in the flue gas to the $CO_2$ capture system.

[e] This selection affects only the cost and performance associated with the added cooling system capacity and does not impact the cost and performance of the $CO_2$ capture system, or other applicable systems, as the references for these systems utilize a wet cooling system.

[f] The state classification is determined based on information provided in the “National Water Summary, Hydrologic Events and Issues.” [21]

Calculations tabs. Additionally, a selection of result categories is presented for each of the scenarios in the Results tabs, on an individual facility basis. The Results tabs provide a location to filter the results for more fine-tuned analyses. These filters will carry through to the charts; however, they will not affect the data reported in the summary table.

### 3.4.1 Summary

The specifications made in the User Input tab shown in Section 3.3 are used to produce the results presented in Exhibit 3-3. The results of the ammonia process are provided as an example, with identical data available for the remaining processes in the IND CCRD. The summary results table also includes a summary of the process assumptions, for convenience. The values listed within this guide are examples only, and numbers within the actual CCRD files may differ due to updated data.

The emissions reported to the EPA for some facilities include $CO_2$ that is currently collected and transferred off-site or injected. These facilities are flagged in the EPA data, and the CCRD assumes that the retrofit design is not applicable to them so they are not available for retrofit. The emissions from these facilities are assumed to be captured and excluded from further calculations.

As shown in Exhibit 3-3, there are a total of 22 ammonia facilities included in the IND CCRD, of those, only 3 are available for retrofit as the remaining facilities already include some degree of $CO_2$ capture and utilization. Of these, none are in a state designated as dry; therefore, a wet cooling system was added to handle the additional cooling load introduced by the $CO_2$ capture system in all facilities.

The average parasitic load and natural gas requirement incurred due to retrofitting the fleet is shown to be 9 MW and 94 MMBtu/hr, respectively. These power requirements, combined with the average capital cost to retrofit of $74 million dollars (on a total overnight cost [TOC] basis) results in an incremental cost of product (COP), including transport and storage (T&S), of $129.3/ton of ammonia.

***Exhibit 3-3. Summary results***

| Parameter | Ammonia | |
|---|---|---|
| | Fleet Total | Unit Average |
| Total facilities, No. | 22 | – |
| Facilities retrofit with CCS, No. | 3 | – |
| Facilities retrofit with dry cooling, No. | 0 | – |
| Pre-retrofit total $CO_2$ emissions, x1,000 TPY | 15,497 | 704 |
| Existing (pre-retrofit) transferred off-site or injected but reported as $CO_2$ emissions (excluded from retrofit), x1,000 TPY | 14,015 | 738 |
| Pre-retrofit uncontrolled $CO_2$ emissions, x1,000 TPY | 1,482 | 494 |
| Post-retrofit $CO_2$ emissions, x1,000 TPY | 50 | 2 |
| Retrofit $CO_2$ capture, x1,000 TPY | 1,432 | 477 |
| Retrofit parasitic load, MW | 27 | 9 |
| Retrofit power requirement, x1,000 MWh/yr | 182 | 61 |
| Retrofit natural gas load, MMBtu/hr | 281 | 94 |
| Retrofit natural gas requirement, x1,000 MMBtu/yr | 1,924 | 641 |
| Retrofit capital cost (TOC), million$ | 221 | 74 |
| Retrofit COP, $/ton product | – | 129.3 |
| Cost of $CO_2$ captured, $/tonne | – | 110 |
| Cost of $CO_2$ avoided, $/tonne | – | 110 |
| **Process Assumptions** | | |
| $CO_2$ capture rate (Source 1), % | 100% | |
| $CO_2$ capture rate (Source 2), % | 90% | |
| Average capacity factor | 78% | |
| Retrofit unit capacity applicability limit, TPD-$CO_2$ | 0 | |
| Retrofit cost factor | 1.05 | |
| Capital charge factor | 0.169 | |
| Maximum $CO_2$ capture rate per train, TPD | Default | |
| Cost year basis | 2018 | |
| Cooling preference | State | |
| Purchased electricity price, $/MWh | Varies | |
| Purchased natural gas price, $/MMBtu | Varies | |
| Additional auxiliary load penalty, kWh/TPD-$CO_2$ | N/A | |
| $CO_2$ transport and storage cost, $/tonne-$CO_2$ | N/A | |

Note: The cost of $CO_2$ avoided and retrofit COP metrics include T&S. The cost of $CO_2$ captured does not

## 3.4.2 Charts

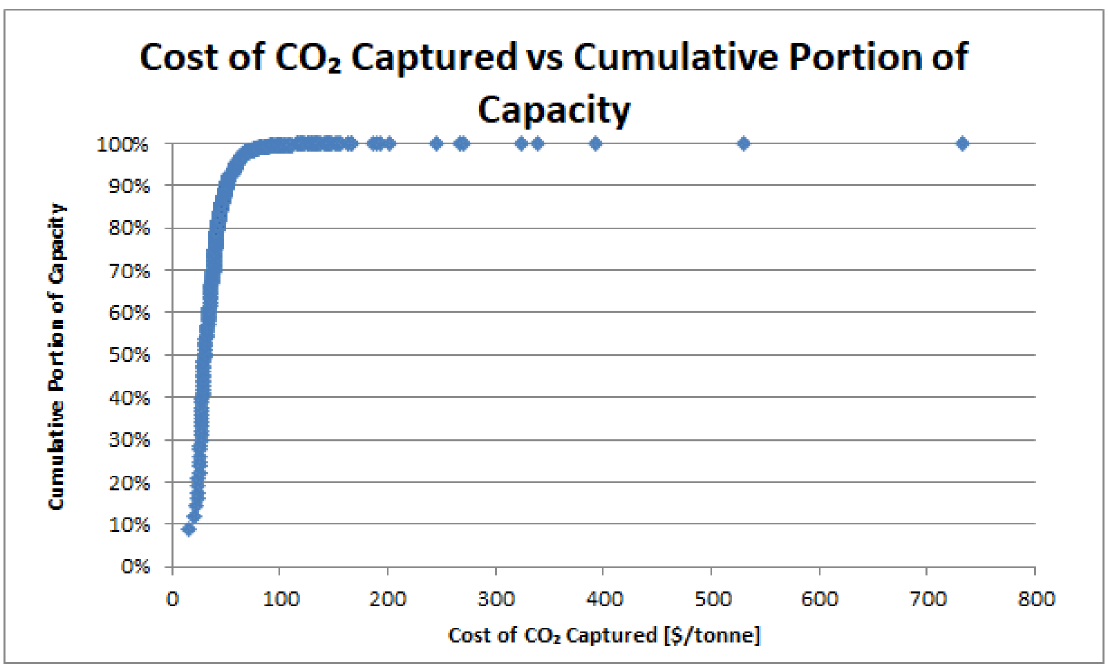
The Charts tab provides convenient chart generation options for several parameters as shown in Exhibit 3-4. By clicking on the parameter desired for the x- and y- axes, a chart similar to that shown in Exhibit 3-5 is generated based on the data from the product Results tabs. By default, the process chart is set to natural gas; however, by clicking on the black cell in the first row labeled “Natural Gas” (range O1:W1), a drop-down list is available to select any of the other processes. A macro is activated for any new selection. If the chart does not seem to reflect recent changes to the data, selecting an alternative option and then reselecting the desired option should rerun the macro and update the chart. When “Cumulative Portion of Capacity” is selected in either the x- or y-axis, the macro sorts the associated columns and temporarily pastes a copy of the required data in columns “Y” through “AC.”  Any data that are present in these columns will be permanently deleted. Only one axis can be set to “Cumulative Portion of Capacity” at a time.

The chart can be adjusted by the user via Excel’s chart menus as needed (e.g., the X-axis bound maximum can be reduced to eliminate outliers).

***Exhibit 3-4. Chart generation parameter options***

| Natural Gas | | |
|---|---|---|
| X-Axis | | Y-Axis |
| Cost of $CO_2$ Captured | | Cost of $CO_2$ Captured |
| Cumulative Capacity | | Cumulative Capacity |
| Cumulative Portion of Capacity | | Cumulative Portion of Capacity |
| Incremental COP | | Incremental COP |
| Cost of $CO_2$ Avoided | | Cost of $CO_2$ Avoided |
| Facility Capacity | | Facility Capacity |

***Exhibit 3-5. Process results example (natural gas)***



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# APPENDIX: INDUSTRIAL SOURCES DATABASE CALCULATIONS

## A.1 UPDATES AND AUTOMATED CALCULATIONS

Each of the carbon capture retrofit databases (CCRDs) are updated annually, where the data in the following tabs are replaced for the industrial (IND) CCRD:

1. Purchased Power Cost
2. EPA GHG Data
3. EPA FLIGHT Data
4. EPA AGR Data
5. CostIndices

A macro is used during the update to draw in data from various tabs and prepare the raw data for use in the Calculations tab. The macro and layout of the Calculations tabs is discussed below.

### *Macro Functions*

Except for the ethanol process, the macro used in the IND CCRD searches the data provided in the Environmental Protection Agency (EPA) Greenhouse Gas (GHG) Data tab for facilities that match the specified "Industry Type (Subparts)," which are: [17]

1. Ammonia – ammonia manufacturing (G)
2. Cement – cement production (H)
3. Hydrogen – petroleum refining (Y) and hydrogen production (P)
4. Natural Gas – natural gas and natural gas liquid supply (W-PROC)

For the ethanol process, the EPA Facility Level Information on GreenHouse gases Tool (FLIGHT) Data tab contains a list of ethanol process facilities, which the macro uses to search for matching facilities in the EPA GHG Data tab.

For the facilities that meet the filter criteria under each of the processes, the macro pastes the facility identification (ID) number in the associated process Calculations tabs.

For the natural gas process, the EPA Envirofacts site contains data on the emissions from acid gas removal systems summarized at the facility level for Petroleum and Natural Gas Systems, which is used within the calculations to determine the applicability of adding the technology to the natural gas processing facilities in the EPA GHG Data tab. The list of facilities for natural gas processing was manually replaced with the list of facilities from the EPA AGR Data tab and the calculations were modified to use only the AGR emissions in the latest update.

Lastly, the macro adjusts all equations to reflect changes made to the size of the reference data tables and adjusts the number of rows in the Calculations and Results tabs to reflect the updated number of facilities.

### *Calculations Tab Layout*

While the information provided in the Calculations tab of each of the five processes (ammonia, cement, ethanol, hydrogen, and natural gas) varies, the organization and layout are consistent.

Each of the sections of the Calculations tab are separated by vertical gray bars, with the first section containing the filtered unit IDs, along with a collection of pertinent raw data required for calculations for each facility.

Based on the parameter selections set in the User Input tab (see Section 3.3), the second section calculates the total $CO_2$ captured for each facility and assigns a wet or dry cooling system to the additional cooling load incurred due to the addition of the $CO_2$ capture system.

The annual product capacity is estimated based on the reported $CO_2$ emissions and the typical ratio of those emissions to the product generation rates. [5] The actual ratio of reported emissions to product capacity may be significantly different for individual operating facilities, so the production capacities calculated in this database may not accurately reflect actual production rates for facilities. The second section also filters the facilities (filtered facilities are shown as blank lines) based on the selected retrofit unit capacity applicability limit and based on if the facility is already capturing any of the produced $CO_2$.

The emissions reported to the EPA for some facilities include $CO_2$ that is currently collected and transferred off-site or injected. These facilities are flagged in the EPA data, and the CCRD assumes that the retrofit design is not applicable to them.

Since the existing facility capacity factors (CF) are not included in the raw data for the industrial facilities, the pre-retrofit capacity factor is assumed to be the 2021 industrial average based on public sources for each industry. [9, 10, 11, 12, 13] This value is used to determine the pre-retrofit size of each facility based on the reported emissions.

Since the existing facility operating costs are not included in the raw data for the industrial facilities, the retrofit is assumed to have no impact on the pre-retrofit operating costs (i.e., existing operating and maintenance [O&M] costs are not included in the retrofit COP).

The remaining sections are discussed in the following subsections:

1. Capital costs
2. O&M costs
3. Parasitic loads
4. Reporting metrics (cost of product [COP], cost of $CO_2$ captured, etc.)

## A.2 Capital Costs

Where possible, the Quality Guidelines for Energy System Studies (QGESS) document "Capital Cost Scaling Methodology" [18] was used for guidance in developing the capital cost methodology. However, the amount of information related to internal performance of each unit/facility is minimal; therefore, the rate of captured $CO_2$ is used for scaling the capital costs for all technologies.

Scaling the capital costs exclusively on the rate of captured $CO_2$ will result in inaccuracies for all technologies in each of the CCRDs. Therefore, these costs are considered to be order of magnitude in accuracy.

The IND CCRD contains a Calculations tab for each process. The equipment associated with the $CO_2$ capture system varies by process and an equipment list is provided in Exhibit A-1.

***Exhibit A-1. $CO_2$ capture system equipment list, by process***

<table>
<tr><th>Process</th><th>Capture/ Purification</th><th>Low Pressure Steam Boiler</th><th>Pre-Cooler</th><th>$CO_2$ Compressors</th><th>After-Cooler</th><th>Cooling Water System</th></tr>
<tr><td>Ammonia Primary Reformer[A]</td><td>x</td><td>x</td><td>x</td><td rowspan="2">x</td><td rowspan="2">x</td><td rowspan="2">x</td></tr>
<tr><td>Ammonia Stripper[B]</td><td></td><td></td><td></td></tr>
<tr><td>Cement[A]</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Ethanol</td><td></td><td></td><td>x</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Hydrogen[A]</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Natural Gas</td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td></tr>
</table>

[A] The exhaust gas from the natural gas-fired low-pressure (LP) steam boiler is combined with the process $CO_2$ product stream prior to the capture system if the user selects the option to include natural gas boiler emissions in the capture feed.
[B] The vent stream from the ammonia stripper is combined with the ammonia primary reformer $CO_2$ product stream prior to the pre-cooler.

The reference cost data for all processes comes from the National Energy Technology Laboratory (NETL) study "Cost of Capturing $CO_2$ from Industrial Sources – Revision 3" [5] (referred to as Industrial Sources).

As the $CO_2$ capture system shown for the ammonia primary reformer flue gas was not originally included in the Industrial Sources study, but was added for the IND CCRD, the costs and performance estimates of the $CO_2$ capture system for the cement process were used as a reference—the feed stream of the cement process had a similar concentration of $CO_2$ as that of the ammonia primary reformer flue gas, and it is assumed that the exhaust gas from the natural gas-fired steam boiler make negligible impact on the composition and operating conditions of the emissions stream.

The capital cost scalars for all systems are calculated as follows:

$$CS = \left(\frac{RCC}{RCR}\right)^{EXP}$$

where:

- CS – capital cost scaler, \$/(lb/hr)
- RCC – reference capital cost, \$
- RCR – reference $CO_2$ capture rate, lb/hr
- EXP – exponent

The capital costs of the $CO_2$ capture system, pre-cooler, $CO_2$ compression system, and after-cooler are adjusted based on the number of trains required, which is dependent on the selections made in Section 3.3, per the equation:

$$NT = ROUND\left(\frac{CR}{MPT}\right)$$

where:

- NT – trains, number
- ROUND – rounds up to nearest whole number
- CR – $CO_2$ capture rate, lb/hr
- MPT – maximum $CO_2$ capture rate per train, lb/hr

The capital costs of each technology are calculated as follows:[g, h, i]

$$CC = RCF * NT * CS * \left(\frac{CR}{NT}\right)^{EXP} * \frac{CY_N}{CY_O} * (1 + CY_A)^{(Y_N - Y_O)}$$

where:

- CC – capital cost, $
- RCF – retrofit cost factor
- NT – total number of trains
- CS – capital cost scaler, $/(lb/hr)
- CR – $CO_2$ capture rate, lb/hr
- EXP – exponent
- $CY_N$ – Chemical Engineering Plant Cost Index (CEPCI) value for selected year
- $CY_O$ – CEPCI value for 2018
- $CY_A$ – average annual increase in CEPCI value, fraction
- $Y_N$ – selected cost year basis
- $Y_O$ – reference cost year basis (currently 2018)

## A.3 O&M COSTS

The O&M costs are calculated by:

$$OM = \frac{ROM}{RTPC} * TPC$$

where:

- OM – incremental O&M costs, $/yr
- ROM – the reference incremental O&M costs,[j] $/yr
- RTPC – reference total plant cost, $
- TPC – facility total plant cost, $

[g] NT is only used when calculating the capital costs of $CO_2$ capture system, pre-cooler, $CO_2$ compression system, or after-cooler.

[h] By default, $Y_N = Y_O$, unless a future year is specified in Section 3.3 as the cost year basis.

[i] If a dry cooling system is required, the wet cooling system capital cost is calculated and then multiplied by 2.2, a capital cost ratio derived from the costs reported in Revision 2 of the Fossil Energy Baseline. [23]

[j] For Fixed O&M, the costs should be at 100 percent CF; for Variable O&M, the costs should be at the operating CF.

## A.4 Parasitic Load

The performance data used as the reference facilities in the IND CCRD is sourced from the Industrial Sources study. [5]

The parasitic load of the wet cooling water system is calculated as:

$$PL = WAD * TAD * CR$$

and the parasitic load of the dry cooling water system is calculated as:

$$PL = \left(DWR * FAL + (1 - FAL)\right) * WAD * TAD * CR$$

where:

- PL – parasitic load, MW
- TAD – total auxiliary load, MWh/lb-$CO_2$
- WAD – ratio of reference wet cooling system auxiliary load to reference auxiliary load, fraction
- CR – $CO_2$ captured, lb/hr
- DWR – dry/wet cooling ratio[k]
- FAL – fan electrical auxiliary load ratio,[l] fraction

The parasitic load of the $CO_2$ capture system is calculated as:

$$PL = (TAD - TAD * WAD) * CR$$

where:

- PL – parasitic load, MW
- TAD – total reference auxiliary load, MWh/lb-$CO_2$
- WAD – ratio of reference wet cooling system auxiliary load to reference auxiliary load, fraction
- CR – $CO_2$ captured, lb/hr

The miscellaneous parasitic loads are a user defined value (see Section 3.3), calculated as:

$$PL = CR * MHR$$

where:

- PL – parasitic load, MW
- CR – $CO_2$ captured, TPD
- MHR – additional auxiliary load penalty, MW/TPD

The total parasitic load (TPL) is the sum of all the applicable parasitic loads (PL) above.

[k] The cooling water system performance ratio of 3.5 is taken from NETL's report "Cost and Performance Baseline for Fossil energy Plants – Volume 3b: Low Rank Coal and Natural Gas to Electricity" [24] and supported by EPA's report EPA-821-R-01-036 [22].

[l] The fan electrical auxiliary load to cooling system auxiliary load ratio varies by process and ranges 0.011–0.200 in the Industrial Sources study. [5]

For the processes that require a natural gas boiler (see Exhibit A-1) for LP steam production, the following equation is used to calculate the natural gas requirement:

$$NGR = RPNG * CR$$

where:

- NGR – natural gas requirement, MMBtu/hr
- RPNG – reference natural gas requirement, MMBtu/lb
- CR – $CO_2$ captured, lb/hr

## A.5 Reporting Metrics

The reporting metrics of interest used in the IND CCRD are the COP, the cost of $CO_2$ captured (formerly known as the breakeven $CO_2$ sales price), and the cost of $CO_2$ avoided (formerly known as the breakeven $CO_2$ emissions penalty). In addition to the cost and performance calculations provided in previous sections, the option to include $CO_2$ transport and storage (T&S) costs in the reporting metrics is available in the User Input tab (see Section 3.3). The methodology of calculating the reporting metrics will be discussed in the following subsections.

### *Production Capacity*

The production capacity of each plant is estimated using the following equation:

$$PC = PCE / PR$$

where:

- PC – industrial product capacity, TPY at 100% CF
- PCE – pre-retrofit $CO_2$ emissions, TPY at 100% CF
- PR – reference reported $CO_2$ emissions to production ratio, fraction [5]

### *Cost of Product*

The cost of product (COP) in units of $/ton of industrial product (i.e., ammonia, cement, ethanol, hydrogen, natural gas) is calculated for each product using the following method.

If the T&S costs are selected to be included in the COP, the following equation is used:

$$TS = (TSC * CR)/PC$$

where:

- TS – $CO_2$ T&S costs, $/ton industrial product
- TSC – reference $CO_2$ transport costs, $/ton $CO_2$
- CR – $CO_2$ captured, TPY at 100% CF
- PC – industrial product capacity, TPY at 100% CF

As the IND CCRD assumes that power is not generated on-site, all power requirements are satisfied by purchasing from the grid. The cost of purchased electricity is calculated as:

$$PPC = EC * CF * TPL * 8760$$

where:

- PPC – purchased power cost, \$/yr
- EC – price of electricity, \$/MWh
- CF – capacity factor, fraction
- TPL – total parasitic retrofit load, MW

For the processes that require Shell's $CO_2$ capture systems (see Exhibit A-1), the following equation is used to calculate the cost of natural gas:

$$PNG = ENC * CF * NGR * 8760$$

where:

- PNG – purchased natural gas, \$/yr
- ENC – price of natural gas, \$/MMBtu
- CF – capacity factor, fraction
- NGR – natural gas requirement, MMBtu/hr

The IND CCRD calculates the impact on the COP that would result from adding $CO_2$ capture technology to each facility. The COP is calculated as:

$$COP = \frac{(PPC + PNG + TVOM + TFOM + TPC * OCM * CCF)}{PC * CF} + TS$$

where:

- COP – cost of product, \$/ton industrial product
- PPC – purchased power cost, \$/yr
- PNG – purchased natural gas cost, \$/yr
- TVOM – annual variable O&M, \$/yr
- TFOM – annual fixed O&M, \$/yr
- TPC – total plant cost, \$
- OCM – owner's cost or TOC/TPC cost basis multiplier
- CCF – capital charge factor, fraction
- PC – industrial product capacity, TPY at 100% CF
- CF – capacity factor, fraction
- TS – $CO_2$ T&S costs, \$/ton industrial product

### *Cost of $CO_2$ Captured*

The cost of $CO_2$ captured represents the minimum $CO_2$ plant gate sales price that will incentivize carbon capture in lieu of a defined reference non-capture plant. If $CO_2$ can be sold at a price greater than the cost of $CO_2$ captured, there is an economic incentive to capture $CO_2$. The value is calculated using the following formula:

$$Cost\ of\ CO_2\ Captured = \frac{(COP - TS) * PC}{CR\ /\ Tonne2Ton}$$

where:

- Cost of $CO_2$ captured, \$/tonne
- COP – cost of product, \$/ton
- TS – $CO_2$ T&S costs, \$/ton
- PC – product capacity, TPY at 100% CF
- CR – $CO_2$ captured, TPY at 100% CF
- Tonne2Ton – Conversion for metric tons to short tons

### *Cost $CO_2$ Avoided*

The cost of $CO_2$ avoided represents the minimum $CO_2$ emissions price that will, when applied to both the capture and non-capture plant, incentivize carbon capture in lieu of a defined reference non-capture plant. If emission penalties or allowance prices are higher than the cost of $CO_2$ avoided, there is an economic incentive to capture $CO_2$. The cost of $CO_2$ avoided is calculated using the following formula:

$$Cost\ of\ CO_2\ Avoided = \frac{(COP) * PC}{(PCE - CR)/\ Tonne2Ton}$$

where:

- Cost of $CO_2$ avoided, \$/tonne
- COP – cost of product, \$/ton
- PC – product capacity, TPY at 100% CF
- PCE – pre-retrofit $CO_2$ emissions, TPY at 100% CF
- CR – $CO_2$ captured, TPY at 100% CF
- Tonne2Ton – Conversion for metric tons to short ton

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