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### ACRONYMS AND ABBREVIATIONS

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<tr>
<th>ABB/ACRONYM</th>
<th>FULL</th>
<th>MFR/ABBREVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB</td>
<td>Allmänna Svenska Elektriska Aktiebolaget Brown Boveri</td>
<td>MATS</td>
</tr>
<tr>
<td>AFB</td>
<td>Atmospheric fluidized bed</td>
<td>MDEA</td>
</tr>
<tr>
<td>BOP</td>
<td>Balance of plant</td>
<td>MMBtu</td>
</tr>
<tr>
<td>Btu</td>
<td>British thermal unit</td>
<td>MTR</td>
</tr>
<tr>
<td>CEPCI</td>
<td>Chemical Engineering Cost Index</td>
<td>MW</td>
</tr>
<tr>
<td>CCRD</td>
<td>Carbon capture retrofit database</td>
<td>MWh</td>
</tr>
<tr>
<td>CCF</td>
<td>Capital charge factor</td>
<td>NERC</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
<td>NETL</td>
</tr>
<tr>
<td>CF</td>
<td>Capacity factor</td>
<td>NGCC</td>
</tr>
<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
<td>NOx</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
<td>NSPS</td>
</tr>
<tr>
<td>COE</td>
<td>Cost of electricity</td>
<td>O&amp;M</td>
</tr>
<tr>
<td>COP</td>
<td>Cost of production</td>
<td>PC</td>
</tr>
<tr>
<td>CT</td>
<td>Combustion turbine</td>
<td>PSFM</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
<td>QGESS</td>
</tr>
<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
<td>SCR</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
<td>SO₂</td>
</tr>
<tr>
<td>EV</td>
<td>Energy Velocity</td>
<td>T&amp;S</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue gas desulfurizer</td>
<td>TDA</td>
</tr>
<tr>
<td>FLIGHT</td>
<td>Facility Level Information on GreenHouse gases Tool</td>
<td>tonne</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
<td>TPC</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
<td>TPD</td>
</tr>
<tr>
<td>IND</td>
<td>Industrial</td>
<td>TPY</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt</td>
<td>U.S.</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
<td></td>
</tr>
<tr>
<td>LP</td>
<td>Low pressure</td>
<td></td>
</tr>
</tbody>
</table>
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1 **INTRODUCTION**

The United States (U.S.) Department of Energy’s (DOE) National Energy Technology Laboratory (NETL) has produced three carbon capture retrofit databases (CCRDs), which contain a collection of units selected from the power generation and industrial sources (IND) sectors located in the United States that are either in operating or standby status. The power generation category is subdivided into the post-combustion (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, hydrogen, and natural gas processing industries.

The plant data for the IND CCRD are sourced from the Environmental Protection Agency’s (EPA) greenhouse gas (GHG) reporting program and the EPA’s Facility Level Information on GreenHouse gases Tool (FLIGHT).

The CCRDs provide high-level analyses on the incremental costs for retrofitting point sources with carbon dioxide (CO₂) capture and/or compression systems. Options are available to include costs of other technological improvements that would be required to comply with various regulations (e.g., Mercury and Air Toxic Standards [MATS] [1] and New Source Performance Standards [NSPS] [2]) when installing CO₂ scrubbing technology.

This report 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 CO₂ 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 Appendix A.

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 power systems financial model (PSFM) [3] was used to generate capital charge factors for use in calculating the cost of product based on recommended financial structures for various project types [4], [5] and the simplified equation, described in the Quality Guidelines for Energy System Studies (QGESS) document “Cost Estimation Methodology for NETL Assessments of Power Plant Performance”, [6] which provides the typical assumptions used in greenfield calculations. Several factors influence the capital charge factors including the interest rate, the required return on equity, the economic life of the plant, the percentage of debt and equity, and the debt term, which is assumed to be half the economic life of the plant for all retrofit cases. [7]

The 150% declining balance method with half-year convention percentages was used to calculate depreciation [8]. 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 5 years, respectively. Shorter plant lives result in higher capital charge factors, whereas shorter depreciation periods result in lower capital charge factors.

For units that require multiple trains of CO\(_2\) removal 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

\(^a\) The accuracy of the reference cost data is considered to be -15%/+30%. [6]
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 [9], [10] and no cost or performance adjustments are 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 CO₂ compressors.

The accuracy of the cooling tower cost and performance is dependent on the accuracy of the CO₂ removal 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 CO₂ emissions is reported for all facilities and no considerations are given for any NOx, SO₂, 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 CO₂ capture system varies by process and an equipment list is provided in Exhibit 2-1.
For processes that utilize an MDEA CO₂ capture unit, the cost and performance of the system is impacted in an identical way as the solvent-based CO₂ capture system for PC and NGCC power generation systems. Namely by variances in composition, dilution, purity, and operating conditions. The IND CCRD may be particularly prone to impurities in the treated gas as no pre-scrubber is included in the MDEA pre-purification design. 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 CO₂ 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.

Only the Cement and Natural Gas processes utilize an integrally-geared centrifugal CO₂ compressor (identical to the PC and NGCC CCRDs), 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 CO₂ production rates outside the recommended operating range of these systems.

1 The vent stream from the ammonia stripper is combined with the ammonia primary reformer CO₂ product stream prior to the pre-cooler.

2 The exhaust gas from the natural gas fired low pressure (LP) steam boiler is combined with the process CO₂ product stream prior to the pre-cooler.
For processes that utilize an MDEA purification unit, a natural gas boiler is included to produce the required steam for the unit’s CO₂ regenerator. The flue gas from this boiler is directly mixed with the CO₂ product stream of the MDEA purification unit with no treatment. It is assumed that this stream is of insufficient size to substantially affect the purity of the mixed stream and that no additional purification systems are required.

Lastly, it was assumed that no by-products were co-produced by any of the processes. However, a significant portion of the CO₂ produced by the facilities could potentially be diverted for this purpose and urea co-production has been noted to be practiced at a number of ammonia process plants. [10]
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 Appendix A.

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 disclaimer tab is hidden and 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 is made visible and all other tabs are hidden.

3.2 LAYOUT

The IND CCRD open to a disclaimer tab that provides a notification that macros must be enabled for the CCRD to operate. A link to a copy of the User Guide is also provided. Upon pressing the “Start Program” button (with macros enabled) and acknowledging that Section 2 of the User Guide has been read, the CCRDs will hide the disclaimer page and 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) CostIndicies
7) Water Availability

The Cost Parameters tabs are used to store 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 CO₂ 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Ammonia</th>
<th>Cement</th>
<th>Ethanol</th>
<th>Hydrogen</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Capture Rate (Source 1)</td>
<td>Choose Option</td>
<td>Default</td>
<td>100%</td>
<td>90%</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>CO₂ Capture Rate (Source 2)</td>
<td>Choose Option</td>
<td>Default</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>Choose Option</td>
<td>Default</td>
<td>78%</td>
<td>66%</td>
<td>102%</td>
<td>91%</td>
<td>61%</td>
</tr>
<tr>
<td>Retrofit Unit Capacity Applicability Limit</td>
<td>Choose Option</td>
<td>Default</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>Retrofit Cost Factor</td>
<td>Choose Option</td>
<td>Default</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Capital Charge Factor</td>
<td>Choose Option</td>
<td>High Risk</td>
<td>0.169</td>
<td>0.194</td>
<td>0.169</td>
<td>0.194</td>
<td>0.169</td>
</tr>
</tbody>
</table>

Note: The names of the industrial processes (Ammonia, Cement, etc.) can be edited here.
The CO₂ capture rate\(^b\) can be set to either 1) default or 2) user input. For processes that capture 100 percent (by default) of the emitted CO₂, the existing source of emissions is nearly pure [10]; therefore, only cooling and compression are required. The processes that capture 90 percent (by default), however, use a methyl diethanolamine (MDEA) solvent-based CO₂ capture system. [10]

While the cost and performance of the MDEA system was taken from the NETL study “Cost of Capturing CO₂ from Industrial Sources – Revision 2” [10] (referred to as Industrial Sources), which has a design capture rate of 95 percent; the default CO₂ capture rate for the IND CCRD was set to 90 percent to be consistent with the NETL program goal used in the Bituminous Baseline. [9]

The capacity factor can be set to either 1) default – which is set based on the 2010 average industry utilization [11], [12], [13], [14], [15] or 2) user input.

The retrofit unit capacity applicability limit can be set to either 1) default – which is 0 TPD-CO₂; 2) 25 MW equivalent – which is set to 534 TPD-CO₂ and represents the theoretical equivalent CO₂ production rate of the Bituminous Baseline’s Case B11A [9], scaled down to 25 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 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 CO₂ capture system at a greenfield facility – which the reference costs used in the IND CCRD were developed for – which the reference costs used in the IND CCRD were developed for.

The capital charge factor can be set to either 1) high risk, 2) conventional, or 3) user input. The CCF can be further defined as having either a 10-, 20-, or 30-year economic life. The default values for the high risk and conventional financing with a 30-year economic life are based on the three-year CCFs reported in the Industrial Sources. [10] The remainder were developed using the PSFM. [3]

\(^b\) Only the ammonia process has a second source, as it represents a modification to the reference ammonia process configuration described in “Cost of Capturing CO₂ from Industrial Sources – Revision 2.” [10] 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-CO₂ as there are currently no regulations controlling CO₂ emissions from industrial processes. Therefore, this is considered an elective selection based on economic viability, which will not have a standard minimum.
### Exhibit 3-2 Advanced user input parameters for the IND CCRD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>Ammonia</th>
<th>Cement</th>
<th>Ethanol</th>
<th>Hydrogen</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum CO₂ Capture Rate Per Train</td>
<td>Choose Option</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>TPD</td>
<td>21,867</td>
<td>27,430</td>
<td>122,453</td>
<td>54,516</td>
<td>121,229</td>
<td></td>
</tr>
<tr>
<td>Cost Year Basis</td>
<td>Choose Option</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>Year</td>
<td>2011</td>
<td>2011</td>
<td>2011</td>
<td>2011</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>Cooling Preference?</td>
<td>Choose Option</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
</tr>
<tr>
<td>Purchased Electricity Price</td>
<td>Choose Option</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
<td>State</td>
</tr>
<tr>
<td></td>
<td>$/MWh</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Purchased Natural Gas Price</td>
<td>Choose Option</td>
<td>State</td>
<td>State</td>
<td>N/A</td>
<td>State</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>$/MMBtu</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Additional Auxiliary Load Penalty</td>
<td>Choose Option</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>kW/TPD-CO₂</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>CO₂ Transport and Storage Costs</td>
<td>Choose Option</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>$/tonne captured</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
The **maximum CO₂ capture rate per train** can be set to either 1) default or 2) user input. If a facility has a CO₂ production rate greater than the maximum per train, multiple trains will be used (CO₂ 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) 2017. By default, the results presented in the CCRD are provided on a 2011-year dollar basis; however, users may also choose to have the results on a 2017-year dollar basis. The calculations use data from the CEPCI \([16]\) to scale the results to the chosen year.

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\(^f\). The cooling system is added to compensate for the increased cooling water flow rate from the CO₂ capture system, where applicable.

The **purchased electricity price** can be set to either 1) state – which uses the state annual average retail sales of electricity to ultimate customers’ price for industrial sectors \([17]\), or 2) user input. This parameter is the cost to purchase additional electricity for the requirements of the equipment associated with the retrofit.

The **purchased natural gas price** can be set to either 1) state – which uses the state annual average price of natural gas delivered to consumers \([18]\), or 2) user input. This parameter is the cost to purchase natural gas for the steam boiler used by the CO₂ capture system, specifically the MDEA unit, to regenerate CO₂. This option is shown as “N/A” for process that only require cooling and compression (no MDEA 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 **CO₂ transport and storage costs** can be set to either 1) none, 2) default – currently $11/tonne, or 3) user input.

---

\(^d\) The default maximum CO₂ capture rate per train is based on the value used in the PC CCRD (described in previous footnote and scaled based on CO₂ concentration in the flue gas to the CO₂ removal 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 CO₂ 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.” \([24]\)
3.4 Results

Based on the selections specified in the User Input (discussed in Section 3.3), results are calculated (discussed in Appendix A) and presented in several forms. All the results of the individual facilities can be accessed in the 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 tab provides 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 Charts

The Charts tab provides convenient chart generation options for several parameters as shown in Exhibit 3-3. By clicking on the parameter desired for the x- and y-axes a chart similar to that shown in Exhibit 3-4 is generated based on the data from the product result 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 when “Cumulative Portion of Capacity” is selected in either the x- or y-axis. This 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.
3.4.2 Summary Table

The specifications made in the User Input tab shown in Section 3.3 are used to produce the results presented in Exhibit 3-5. 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.

As shown in Exhibit 3-5, 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 CO₂ 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 CO₂ 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 $76 million dollars (on a TOC basis) results in an incremental cost of production (COP) of $52.5/ton.
**Exhibit 3-5 Summary results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Fleet</td>
</tr>
<tr>
<td>Total facilities, No.</td>
<td>22</td>
</tr>
<tr>
<td>Facilities retrofit with CCS, No.</td>
<td>3</td>
</tr>
<tr>
<td>Facilities retrofit with dry cooling, No.</td>
<td>0</td>
</tr>
<tr>
<td>Pre-retrofit total CO₂ emissions, x1,000 TPY</td>
<td>15,497</td>
</tr>
<tr>
<td>Existing (pre-retrofit) transferred off-site or injected but reported as CO₂ emissions (excluded from retrofit), x1,000 TPY</td>
<td>14,015</td>
</tr>
<tr>
<td>Pre-retrofit uncontrolled CO₂ emissions, x1,000 TPY</td>
<td>1,482</td>
</tr>
<tr>
<td>Post-retrofit CO₂ emissions, x1,000 TPY</td>
<td>50</td>
</tr>
<tr>
<td>Retrofit CO₂ capture, x1,000 TPY</td>
<td>1,432</td>
</tr>
<tr>
<td>Retrofit parasitic load, MW</td>
<td>27</td>
</tr>
<tr>
<td>Retrofit power requirement, x1,000 MWh/yr</td>
<td>182</td>
</tr>
<tr>
<td>Retrofit natural gas load, MMBtu/hr</td>
<td>281</td>
</tr>
<tr>
<td>Retrofit natural gas requirement, x1,000 MMBtu/yr</td>
<td>1,924</td>
</tr>
<tr>
<td>Retrofit capital cost (TOC), million$</td>
<td>221</td>
</tr>
<tr>
<td>Retrofit COP, $/TPY</td>
<td>–</td>
</tr>
<tr>
<td>Breakeven CO₂ Sales Price, $/tonne</td>
<td>–</td>
</tr>
<tr>
<td>Breakeven CO₂ Emissions Penalty, $/tonne</td>
<td>–</td>
</tr>
</tbody>
</table>

**Process Assumptions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ capture rate (Source 1), %</td>
<td>100%</td>
</tr>
<tr>
<td>CO₂ capture rate (Source 2), %</td>
<td>90%</td>
</tr>
<tr>
<td>Average capacity factor</td>
<td>78%</td>
</tr>
<tr>
<td>Retrofit unit capacity applicability limit, TPD-CO₂</td>
<td>0</td>
</tr>
<tr>
<td>Retrofit cost factor</td>
<td>1.05</td>
</tr>
<tr>
<td>Capital charge factor</td>
<td>0.169</td>
</tr>
<tr>
<td>Maximum CO₂ capture rate per train, TPD</td>
<td>Default</td>
</tr>
<tr>
<td>Cost year basis</td>
<td>2011</td>
</tr>
<tr>
<td>Cooling preference</td>
<td>State</td>
</tr>
<tr>
<td>Purchased electricity price, $/MWh</td>
<td>N/A</td>
</tr>
<tr>
<td>Purchased natural gas price, $/MMBtu</td>
<td>N/A</td>
</tr>
<tr>
<td>Additional auxiliary load penalty, kWh/TPD-CO₂</td>
<td>N/A</td>
</tr>
<tr>
<td>CO₂ transport and storage cost, $/tonne-CO₂</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Note: The breakeven CO₂ emissions penalty includes T&S. The breakeven CO₂ sales price does not.
4 References


**APPENDIX: CALCULATIONS**

**A.1 UPDATES AND AUTOMATED CALCULATIONS**

Each of the 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

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 tab 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:

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 (NN)

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 ID number in the associated process Calculation tab.

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 tabs 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 CO₂ captured for each facility and assigns a wet or dry cooling system to the additional cooling load incurred due to the addition of the CO₂ capture system. The annual product capacity is estimated based on the reported CO₂ emissions and the typical ratio of those emissions to the product generation rates. [10] 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 CO₂.

The emissions reported to the EPA for some facilities include CO₂ 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 factor (CF) and operating costs are not included in the raw data for the industrial facilities, the user input value is assumed to apply to both pre-retrofit and post-retrofit operations and the retrofit is assumed to have no impact on the pre-retrofit operating costs (i.e. existing O&M costs are not included in the retrofit COP).

The remaining sections are discussed in subsequent sections of this report:

1) Capital costs
2) O&M costs
3) Parasitic loads
4) Reporting metrics (cost of production (COP), breakeven CO₂ sales price, etc.)

A.2 Capital Costs

Where possible, the QGESS document “Capital Cost Scaling Methodology” [19] 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 CO₂ is used for scaling the capital costs for all technologies.

Scaling the capital costs exclusively on the rate of captured CO₂ 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 calculation tab for each process. The equipment associated with the CO₂ capture system varies by process and an equipment list is provided in Exhibit A-1.
**Exhibit A-1 CO₂ capture system equipment list, by process**

<table>
<thead>
<tr>
<th>Process</th>
<th>MDEA Purification</th>
<th>Low Pressure Steam Boiler</th>
<th>Pre-Cooler</th>
<th>CO₂ Compressors</th>
<th>After-Cooler</th>
<th>Cooling Water System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia Primary Reformer²</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Ammonia Stripper¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement²</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>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen²</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ The vent stream from the ammonia stripper is combined with the ammonia primary reformer CO₂ product stream prior to the pre-cooler.
² The exhaust gas from the natural gas fired low pressure (LP) steam boiler is combined with the process CO₂ product stream prior to the pre-cooler.

The reference cost data for all processes comes from the Industrial Sources study. [10]

As the CO₂ 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 reported for the cement process were used as a reference – the feed stream of the cement process had a similar concentration of CO₂ as that of the ammonia primary reformer flue gas.

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

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

where:
- \( CS \) – capital cost scaler, ($/hr)/lb
- \( RCC \) – reference capital cost, $
- \( RCR \) – reference CO₂ capture rate, lb/hr
- \( EXP \) – exponent

The capital costs of the CO₂ removal system, pre-cooler, CO₂ 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
- \( CR \) – CO₂ capture rate, lb/hr
- \( MPT \) – maximum CO₂ capture rate per train, lb/hr
The capital costs of each technology are calculated as follows\textsuperscript{g,h,i}: 

\[
CC = RCF \times NT \times CS \times \left(\frac{CR}{NT}\right)^{EXP} \times \frac{CY_N}{CY_O} \times (1 + CY_A)^{(YN-YO)}
\]

where:

- CC – capital cost, $
- RCF – retrofit cost factor
- NT – total number of trains
- CS – capital cost scaler, ($*hr)/lb
- CR – CO\textsubscript{2} capture rate, lb/hr
- EXP – exponent
- CY\textsubscript{N} – CEPCI value for selected year
- CY\textsubscript{O} – CEPCI value for 2011
- CY\textsubscript{A} – average annual increase in CEPCI value, fraction
- Y\textsubscript{N} – selected cost year basis
- Y\textsubscript{O} – reference cost year basis (currently 2011)

\textbf{A.3 Operating and Maintenance Costs}

The O&M costs are calculated by:

\[
OM = \frac{ROM}{RTPC} \times TPC
\]

where:

- OM – the ratio of the reference O&M costs relative to the reference TPC, 1/yr
- ROM – the reference incremental O&M costs\textsuperscript{j}, $/yr
- RTPC – reference total plant cost, $
- TPC – facility total plant cost, $

\textbf{A.4 Parasitic Load}

The performance data used as the reference facilities in the IND CCRD is sourced from the Industrial Sources study. [10]

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

\[
PL = WAD \times TAD \times CR
\]

\textsuperscript{g} NT is only used when calculating the capital costs of CO\textsubscript{2} removal system, pre-cooler, CO\textsubscript{2} compression system, or after-cooler.

\textsuperscript{h} By default, Y\textsubscript{N} = Y\textsubscript{O}, unless a future year is specified in Section 3.3 as the cost year basis.

\textsuperscript{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 Bituminous Baseline. [25]

\textsuperscript{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.
and the parasitic load of the dry cooling water system is calculated as:

\[ PL = (DWR \times FAL + (1 - FAL)) \times WAD \times TAD \times CR \]

where:
- PL – parasitic load, MW
- TAD – total reference auxiliary load, MWh/lb-CO₂
- WAD – ratio of reference wet cooling system auxiliary load to reference TAD, fraction
- CR – CO₂ captured, lb/hr
- DWR – dry/wet cooling ratio\(^k\)
- FAL – fan electrical auxiliary load ratio\(^l\), fraction

The parasitic load of the CO₂ capture system is calculated as:

\[ PL = (TAD - TAD \times WAD) \times CR \]

where:
- PL – parasitic load, MW
- TAD – total reference auxiliary load, MWh/lb-CO₂
- WAD – ratio of reference wet cooling system auxiliary load to reference TAD, fraction
- CR – CO₂ captured, lb/hr

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

\[ PL = CR \times MHR \]

where:
- PL – parasitic load, MW
- CR – CO₂ captured, TPD
- MHR – additional auxiliary load penalty, MW/TPD

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:

\[ NGR = RPNG \times CR \]

where:
- NGR – natural gas requirement, MMBtu/hr
- RPNG – reference natural gas requirement, MMBtu/lb
- CR – CO₂ captured, lb/hr

\(^k\) 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” [27] and supported by the EPA’s report EPA-821-R-01-036. [26]

\(^l\) The fan electrical auxiliary load to cooling system auxiliary load ratio varies by process and ranges from 0.011 to 0.200 in the Industrial Sources study. [10]
A.5 Reporting Metrics

The reporting metrics of interest used in the IND CCRD are the COP, the breakeven CO₂ sales price (formerly known as the cost of CO₂ captured), and the breakeven CO₂ emissions penalty (formerly known as the cost of CO₂ avoided). In addition to the cost and performance calculations provided in previous sections, the option to include CO₂ 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:

\[ PC = \frac{PCE}{PR} \]

where:
- PC – product capacity, TPY at 100% CF
- PCE – pre-retrofit CO₂ emissions, TPY at 100% CF
- PR – reference reported CO₂ emissions to production ratio, fraction

Cost of Production

The cost of production (COP) in units of $/ton of product is calculated for each product using the following method. The cost of production (COP) in units of $/ton of product 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:

\[ TS = \frac{(TSC \times CR)}{PC} \]

where:
- TS – CO₂ T&S costs, $/ton
- TSC – reference CO₂ transport costs, $/ton
- CR – CO₂ captured, TPY at 100% CF
- PC – 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:

\[ PPC = EC \times CF \times TPL \]

where:
- PPC – purchased power cost, $/hr
- EC – price of electricity, $/MWh
- CF – capacity factor, fraction
- TPL – parasitic retrofit load, MW
For the processes that require methyl diethanolamine (MDEA) purification (see Exhibit A-1), the following equation is used to calculate the cost of natural gas:

\[ PNG = ENC \times CF \times NGR \]

where:
- PNG – purchased natural gas, \$/hr
- ENC – price of natural gas, \$(\text{hr})/\text{MMBtu}
- CF – capacity factor, fraction
- NGR – natural gas requirement, \text{MMBtu/hr}

The IND CCRD calculates the impact on the COP that would result from adding CO₂ capture technology to each facility. The COP is calculated as:

\[ COP = \frac{(PPC + PNG + TVOM + TFOM + TPC \times OCM \times CCF)}{PC \times CF} + TS \]

where:
- COP – cost of production, \$/ton
- PPC – purchased power cost, \$/hr
- PNG – purchased natural gas cost, \$/hr
- TVOM – annual variable O&M, \$/hr
- TFOM – annual fixed O&M, \$/hr
- TPC – total plant cost, 
- OCM – owners cost or TOC/TPC cost basis multiplier
- CCF – capital charge factor, fraction
- PC – product capacity, TPY at 100% CF
- CF – capacity factor, fraction
- TS – CO₂ T&S costs, \$/ton

**Breakeven CO₂ Sales Price**

The breakeven CO₂ sales price represents the minimum CO₂ plant gate sales price that will incentivize carbon capture in lieu of a defined reference non-capture plant. The value is calculated using the following formula:

\[ BEP = \frac{(COP - TS) \times PC}{CR / \text{Tonne2Ton}} \]

where:
- BEP – breakeven CO₂ emissions penalty, \$/tonne
- COP – cost of production, \$/ton
- TS – CO₂ T&S costs, \$/ton
- PC – product capacity, TPY at 100% CF
- CR – CO₂ captured, TPY at 100% CF
- Tonne2Ton – Conversion for metric tons to short tons
**Breakeven CO₂ Emissions Penalty**

The breakeven CO₂ emissions penalty represents the minimum CO₂ 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. The breakeven CO₂ emissions penalty is calculated using the following formula:

\[
BEP = \frac{(COP) \times PC}{(PCE - CR) / \text{Tonne2Ton}}
\]

where:
- BEP – breakeven CO₂ emissions penalty, $/tonne
- COP – cost of production, $/ton
- PC – product capacity, TPY at 100% CF
- PCE – pre-retrofit CO₂ emissions, ton/hr
- CR – CO₂ captured, ton/hr
- Tonne2Ton – Conversion for metric tons to short tons
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Mark Woods
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