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# Acronyms and Abbreviations

Please edit this list to include only acronyms/abbreviations used in this report.

atm Atmosphere (14.696 psi)

bbl Barrel

Btu British thermal unit

CCS Carbon capture and storage

CF Capacity factor

CFR Code of Federal Regulations

CH4 Methane

cm Centimeter

CO Carbon monoxide

CO2 Carbon dioxide

CO2e Carbon dioxide equivalent

COE Cost of electricity

DOE Department of Energy

EIA Energy Information Administration

EOR Enhanced oil recovery

EPA Environmental Protection Agency

FE Fossil energy

FGD Flue gas desulfurization

ft Foot

gal Gallon

GHG Greenhouse gas

GJ Gigajoule

gpm Gallons per minute

h, hr Hour

H2 Hydrogen

H2O Water

Hg Mercury

HHV Higher heating value

hp Horsepower

IEA International Energy Agency

ISO International Organization for Standardization

K Thousand

kg Kilogram

kJ Kilojoule

kW, kWe Kilowatt electric

kWh Kilowatt-hour

lb Pound

LCA Life cycle analysis

m Meter

M Thousand

m3/min Cubic meters per minute

Mcf Thousand cubic feet

mD Millidarcy

MM Million

mol% Mole percent

MPa Megapascal

MW, MWe Megawatt electric

MWh Megawatt-hour

N/A Not applicable/available

N2 Nitrogen

N2O Nitrous oxide

NEMS National Energy Modeling System

NETL National Energy Technology Laboratory

NG Natural gas

NGCC Natural gas combined cycle

NOAK Nth of a kind

NOx Oxides of nitrogen

O&M Operation and maintenance

O2 Oxygen

PC Pulverized coal

ppm Parts per million

PSFM Power Systems Financial Model

psi Pounds per square inch

psia Pound per square inch absolute

psig Pound per square inch gauge

R&D Research and development

SC Supercritical

scf Standard cubic feet

SO2 Sulfur dioxide

SOA State of the art

SOx Oxides of sulfur

tonne Metric ton (1,000 kg)

U.S. United States

°C Degrees Celsius

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# Report Template Instructions

This template shall be utilized for the documentation of the life cycle analysis completed by the Principal Investigators (PIs) to satisfy the requirements of their award. PIs shall report using the structure defined in this template. These sections are required by Section 6 of the Carbon Dioxide Utilization Life Cycle Analysis Guidance for the United States Department of Energy Office of Fossil Energy (i.e., the NETL CO2U LCA Guidance Document). Additional information beyond the minimum reporting requirements may also be included.

Each of the sections included in this report includes template text (designated without highlight) for review and completion by the PIs, and instructions (designated with gray highlight, to be deleted after reading) for completing the corresponding sections.

# Executive Summary

This life cycle analysis (LCA) is being commissioned for the United States (U.S.) Department of Energy (DOE) National Energy Technology Laboratory (NETL) to satisfy the award requirements for Funding Opportunity Announcement (FOA) INSERT FOA NUMBER and TITLE. The Principal Investigators (PIs) for this project are INSERT NAMES and AFFILIATIONS. This LCA report has been prepared in accordance with ISO 14040/14044 requirements for public release of comparative assessments for third parties.

Provide a high level one- to three-page overview of the study goal and scope, key modeling assumptions, results interpretation, and any data limitations that effect the results interpretation. A simplified system boundary with reference flows between key processes or life cycle stages shall be included to quickly communicate the Proposed Product System and Comparison Product System modeled, demonstrate that both systems provide the same service or function to society (both systems have the same functional unit existing the system boundary), and to assist in the interpretation of results. A brief description of the Proposed Product System and Comparison Product System shall be provided with a clear definition of the current Technology Readiness Level (TRL) for the project. Any alternative product systems recommended by the PIs for consideration shall also be included in the Executive Summary with the NETL default modeling product system.

The PIs shall state which product system representation they recommend for project evaluation with accompanying justification. If any proprietary information is obscured or withheld from the report, it shall be noted.

# Goal and Scope

## Study Goal

The purpose of this section is to describe why the study was conducted, how the information/results will be used, by whom, and if the study is intended to be made public.

These goals are generally the same for all United States Department of Energy Carbon Utilization projects. Slight variations based on the Technology Readiness Level (TRL) of the project exist and shall be clarified in this section of the report. For example, the primary purpose of projects with a TRL of 1 through 4 is technology improvement with DOE (the project funder) as the key audience. Projects with a TRL of 5 or higher focus on demonstrating the commercial viability and environmental acceptance of the project with DOE and external stakeholders (i.e., investors) as the key audience. Additional product systems considering broader national and/or international market effects based on varying levels of market penetration shall be included for projects with a TRL of 5 or higher. This shall be described in the goal of the study.

The specific goals of this life cycle analysis (LCA) are described below:

1. Intended application – The intended application of this LCA is to compare the life cycle greenhouse gas (GHG) impact of the proposed project – ADD DESCRIPTION, as modeled of a *Proposed Product System*, to a *Comparison Product System*.
2. Reasons for carrying out the study – To understand how the environmental impact (measured as life cycle GHG impact) of the PROJECT NAME life cycle compares to the life cycle of a system that produces the same products.
3. Intended audience – The intended audience for the LCA described herein is the United States (U.S.) Department of Energy (DOE) Carbon Utilization Program.
4. Public disclosure – The LCAs conducted as part of the U.S. DOE Funding Opportunity Announcement (FOA) requirement will become part of the public record for the award within the final scientific/technical report.

## Study Scope

The purpose of this section of the report is to define what was modeled, what the data quality/representative goals are, what the basis of comparison is in terms of the functional unit (inclusive of all coproducts), and how the results are to be compared. This section also defines the level of completeness required to make a comparison between the Proposed Product System and Comparison Product System. Expectations for sensitivity and uncertainty analysis shall also be described in this section. Variability between U.S. DOE Carbon Utilization projects is expected based on TRL status, project complexity, and expected market effects.

### Functional Unit of the Study

* 1. Describe the product outputs of the Proposed Product System—define the functional unit; more than one product may be produced within the system boundary; in these cases the functional unit is considered a “multiproduct functional unit”
  2. Describe the product outputs of the Comparison Product System—they must meet the same function or service provided to society by all of the coproducts produced within the Proposed Product System

### System Boundary

1. Describe the life cycle stages included and excluded (if applicable) from the study
2. Provide an illustrative depiction of the process flow diagram for both the Proposed Product System and Comparison Product System; key material and energy inputs, reference flows, and the functional unit shall be included on the diagram describing the system boundary

### Carbon Dioxide Source

1. Define the source and CO2 quality properties as received by the utilization project site
   1. Flue gas diversion
      * 1. Sourced from existing power plant (subcritical pulverized coal power plant)
        2. Sourced from a greenfield [new construction] power plant (supercritical pulverized coal power plant)
   2. Captured CO2
      * 1. Existing plant derate
        2. Existing plant external auxiliary power/steam facility
        3. Greenfield [new construction] power plant (supercritical pulverized coal power plant)

### Technology Representativeness

1. Describe the state of the Proposed Product System based on the current research and development performance at the stated TRL
2. Describe any performance adjustments required to represent commercial performance expectations for alternative product systems modified to represent commercial/market performance
   1. TRL 1–4 projects shall describe how research will enable commercial performance expectations; an alternate product system based on the current performance shall be provided to measure progress towards improved environmental performance; comparison of interest will be based on the anticipated commercial performance specifications specified for the technology representativeness
   2. TRL 5 or higher projects are closer to commercial performance specifications, if significant difference exist, these shall be described and an alternative scenario presented similar to TRL 1–4 projects
3. Market share is considered part of the technology representativeness; clearly describe any scenarios or sensitivity requirements for evaluating market effects
   1. National Energy Technology Laboratory (NETL) default scenario for TRL 1–4 projects is one carbon utilization production facility; minimal to no market consequence for elastic markets (electricity production is an inelastic market; therefore, these market effects shall be included for all projects)
   2. NETL default scenario for TRL 5 or higher shall include market effects based on a market analysis; alternative product systems or sensitivity scenarios shall be included to describe the uncertainty in the results from market share assumptions; justify the selection of the preferred market share case for consideration
4. Comparison Product System corresponding technology representativeness shall be based on the marginal-cost technology for each product in the market today; no assumptions about alternative technology learning are required unless knowledge exists regarding significant technological advances within the existing product sector
   1. TRL 1–4 projects may specify in the *Study Scope* that either “*best-in-class technology* (GHG performance)” or “industry standard practice technology” profiles are acceptable in the absence of market information
   2. TRL 5 or higher projects shall use marginal-cost technology; deviations shall be considered a reduction in data quality and described in the data limitations section accompanying the study results

### Geographical Representativeness

1. All Carbon Dioxide Utilization (CO2U) projects and their products shall be produced and consumed in the United States of America
2. Document the physical location of CO2 source and CO2U production facility; the geographical representativeness shall be described as unknown (national), regional, or site specific; supporting supply chain data sources shall reflect known supply chain geographical locations; if unknown, U.S. profiles shall be used in alignment with the defined geographical scope
3. Document the geographical representativeness of each primary life cycle stage/supply chain; any key deviations shall be noted and explained (e.g., use of foreign profile to describe U.S. operations)

### Temporal Representativeness

1. Define the expected production start year and service life of each product produced from the Proposed Product System; high variability is expected between different CO2U projects—adequately describe why the temporal boundaries (study period) was defined for the LCA study
2. Define if the carbon embedded in the CO2U products, if applicable, will remain in a sequestered (not released to the atmosphere) state or not; if not, define the service life of each product and how the carbon will be released to the atmosphere; carbon expected to be retained in the product for greater than 100 years is considered permanently sequestered for the purposes of LCA modeling within this guidance document
3. Generally, the study period is defined by the service life of the primary product of interest from the Proposed Product System; alternative selections of study period are acceptable with justification

### Life Cycle Impact Assessment Methods for Results Interpretation

This study utilizes the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 method combined with the latest global warming potential (GWP) factors included in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) report. The following impact categories have been modeled and are included in this report:

1. GWP (kg CO2e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100
2. OPTIONAL (delete if not modeled) - GWP (kg CO2e), based on IPCC AR5, 20-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-20
3. OPTIONAL (delete if not modeled) - Non-GHG impact assessment method
   1. acidification potential (kg SO2e); abbreviation: AP
   2. particulate matter formation potential (kg PM2.5e); abbreviation: PMFP
   3. photochemical smog formation potential (kgO3e); abbreviation: PSFP
   4. eutrophication potential (kg Ne); abbreviation: EP
   5. ozone depletion potential (kg CFC-11e); abbreviation: ODP
   6. optional: water consumption (l); abbreviation: WC
   7. others

### Completeness Requirements

1. Document the carbon and energy inputs and outputs to the system boundary
2. Document the environmental relevance—all life cycle emission that would contribute to each life cycle impact assessment category that would change the results at the third decimal place (significant digit)

### Sensitivity and Uncertainty Analysis

1. Describe the expectations for how sensitivity and uncertainty will be modeled within the study
2. NETL minimum for sensitivity analysis is to vary each parameter in the model by one increment to determine degree of influence on the study results; highly sensitive parameters shall be evaluated to determine at what level a change in the parameter would result in a change in study conclusions (interpretation of LCA results)
3. NETL minimum expectations is to bracket the data uncertainty and technical variability of the key modeling parameters to define “low” and “high” scenarios that bracket the “expected” result from the recommended parameters/technical performance; this approach results in three discrete LCA results for each Proposed Product System and Comparison Product System modeled
4. Describe under what modeling conditions the results of the LCA study would change the outcome of the comparison

# Life Cycle Inventory Analysis

The purpose of this section is to document how the life cycle of the Proposed Product System and Comparison Product System were modeled in accordance with the goal and scope of the study. This section provides the transparency on data sources used, calculations or other data conversions performed, and validation (completeness and sensitivity checks) to demonstrate that the life cycle inventory (LCI) model meets the goal and scope of the LCA. If not, the data limitations shall be adequately described and explained to determine in the results interpretation section if they are significant or insignificant to the study comparison.

## Modeling Platform

Define and describe the modeling option utilized and describe and enumerate the supporting files that are provided in addition to this report.

1. openLCA
   1. Modified **NETL CO2U openLCA LCI Database** with project LCA and sensitivity/uncertainty analysis
   2. Completed **NETL CO2U openLCA Results Contribution Tool**
   3. Completed **NETL CO2U LCA Report Template**
2. PI spreadsheet model
   1. Completed **NETL CO2U LCA Documentation Spreadsheet** and supporting materials used outside of the software (e.g., results interpretation spreadsheets)
   2. Completed **NETL CO2U LCA Report Template**
3. Third-party LCA software
   1. Submit LCA data via one of the two methods:
4. Provide final LCA model database file and supporting materials used outside of the software (e.g., results interpretation spreadsheets) with NETL
5. If PIs do not want to provide the LCA model database, submit a completed **NETL CO2U LCA Documentation Spreadsheet** and supporting materials used outside of the software (e.g., results interpretation spreadsheets)

## Unit Process Descriptions

1. Each unit process shall be described with respect to the scope, purpose, reference flow, key modeling parameters, and connectivity to other unit processes within the life cycle model (required)
2. A unit process “map” or “organizational hierarchy” that aligns to the system diagram is helpful to ensure transparency of how the model was assembled—this can be completed and submitted by using the **NETL CO2U LCA Documentation Spreadsheet**

## Data Sources and Quality Assessment

1. Document the source of each piece of data used in the analysis
2. Describe the sources of data
   1. PI-provided data – describe how the data was collected and why it is representative of the process of interest
   2. Third-party data – describe the source and why it is representative of the process of interest
3. Describe if the data used meets the technical, geographical, and temporal representativeness requirements defined in the *Study Scope*; deficiencies shall be identified for inclusion in the uncertainty analysis section of the results interpretation
   1. This can be accomplished within each unit process description or provided in a summary data quality table for each product system proposed in the study
4. Ensure the above is completed for the “Low,” “Expected,” and “High” modeling scenarios

## Results of Inventory Completeness Check

1. Demonstrate that the model for each product system and related scenarios meet the carbon and energy balance requirements of the completeness check; at a minimum, provide a model level summary in the report; if the model is intended to be included with the Final Scientific/Technical Report, then only a reference to the model is required for documentation
2. Describe any exclusions of unit processes or supporting supply chains resulting from the use of cut-off criteria for each product system

## Results of Life Cycle Inventory Model Sensitivity Check

1. Document the relative sensitivity of key model parameters on the LCI results
2. Include model parameters with significant sensitivity in the results interpretation to determine the effect on the final study results

## Allocation Procedures (Optional)

1. NETL default is system expansion to avoid allocation at the system level; allocation is applied to the LCA study results as an alternative results interpretation; the allocation methods applied shall be clearly documented with justification for selection thereof

# Life Cycle Impact Assessment

The purpose of this section is to document the impact assessment methods defined in the *Study Scope* to be included in the analysis. The NETL minimum requirement is life cycle GHG analysis using the IPCC AR5, 100-year time horizon characterization factors. A table of the factors used in the analysis shall be included in this section of the report.

PIs have the option to include additional environmental metrics to improve the understanding of environmental performance of the CO2U project when compared to existing commercial offerings. NETL has provided a set of additional midpoint impact indicators for consideration. The PIs shall provide a brief description of each impact assessment method used in this section of the report. If openLCA is used as the basis of the impact assessment characterization factors and the model will be part of the Final Scientific/Technical Report, then it is not necessary to reproduce the impact assessment factors in the LCA report. If the openLCA model will not be part of the Final Scientific/Technical Report, then the PIs must include a table of the characterization factors for each impact assessment category considered within the LCA. The midpoint impact assessment characterization factors may be included in an appendix to the report to ensure model transparency.

## Life Cycle Impact Assessment Methods

1. Describe each life cycle impact assessment method applied in the LCA
2. Provide full documentation and justification of custom impact assessment methods

The 100-year GWP factors for CO2, CH4, and N2O utilized in this analysis are depicted in **Exhibit 3‑1**.

Exhibit 3‑1. IPCC AR5 GWPs [1]

|  |  |  |  |
| --- | --- | --- | --- |
| GHG | 20-year | 100-year | Units |
| CO2 | 1 | 1 | kg CO2e |
| CH4 | 87 | 36 | kg CO2e |
| N2O | 268 | 298 | kg CO2e |
| SF6 | 17,500 | 23,500 | kg CO2e |

This analysis utilizes the latest factors available in TRACI 2.1, with modified *characterization factors* for GWP to reflect the current state of science from the IPCC. The following describes the non-GWP midpoint impact assessment categories included in this analysis:

* **Acidification Potential (AP):** The increased concentration of hydrogen ions in a local environment. This can be from the direct addition of acids, or by indirect chemical reactions from the addition of substances such as ammonia. [14] Reporting units are kg SO2‑equivalent.
* **Eutrophication Potential (EP):** The “enrichment of an aquatic ecosystem with nutrients (nitrogen, phosphorus) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass.” [16] Reporting units are kg nitrogen (N)‑equivalent.
* **Photochemical Smog Formation Potential (PSFP):** Ground-level ozone, formed by the reaction of NOx and volatile organic compounds (VOCs) in the presence of sunlight. [14] Reporting units are kg trichlorofluoromethane (CFC-11)-equivalent.
* **Ozone Depletion Potential (ODP):** The deterioration of ozone within the stratosphere by chemicals such as CFCs. Stratospheric ozone provides protection for people, crops, and other plant life from radiation. [14] Reporting units are kg ozone (O3)-equivalent.
* **Particulate Matter Formation Potential (PMFP):** Particulate matter (PM) includes “a mixture of solid particles and liquid droplets found in the air” that are smaller than 10 microns in diameter. [17] Smaller diameter particulate matter (2.5 microns or smaller) can be formed by chemical reactions in the atmosphere (e.g., SO2 and NOx). Almost all PM impacts are caused by PM 2.5 microns or smaller (PM2.5). [18] Reporting units are kg PM2.5-equivalent.
* **Water Consumption (WC):** Water consumption is measured as the volume difference between water withdrawal and discharge and is measured in units of liters (l).

## Data Quality Assessment

1. Describe any known data limitations or omissions of inventory data that may affect the interpretation of each impact categories result
2. Check the completeness based on environmental relevance for each impact category and document the findings; note: deficiencies shall be resolved through additional data collection, bounded with uncertainty in the “Low” and “High” scenarios, and/or documented as a key data limitation to inform the results interpretation
   1. Describe that the completeness was tested and determined not to affect the interpretation of results for each impact category is sufficient; if deficiencies do impact the results interpretation this shall also be noted

## Life Cycle Impact Assessment Results

1. Impact assessment results for each product system modeled in the study shall be documented in this section with an assessment of the key drivers that influence the environmental result for each impact category
2. Recommend providing detailed results by product system in an appendix and comparing the Proposed Product System and Comparison Product System results for key life cycle stages in the *Life Cycle Interpretation* section of the report

# Life Cycle Interpretation

The purpose of this section is to document the comparative results of the LCA study, assess the effect of any data limitations, and provide a concluding assessment of the study findings with recommendations to improve the accuracy and reduce the uncertainty of the results. The life cycle interpretation phase of an LCA is an iterative process of assessing the data quality, refining the LCI modeling as necessary, and determining if sufficient data exists to produce and compare impact assessment results for each impact category proposed in the *Study Scope*. At a minimum, the comparative LCA must be capable of comparing the GHG emissions to meet the primary goal of the LCA.

1. Compare the Proposed Product System to the Comparison Product System and calculate the following result interpretations for GWP (kg CO2e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100 (required)
   1. Stacked bar chart with uncertainty bars
   2. Ratio of Proposed Product System/Comparison Product System
   3. Percent change calculation of the Proposed Product System from the Comparison Product System
2. Describe any data limitations with the model or data for both the Proposed Product System and Comparison Product System; discuss the effect on the interpretation of results
3. Discuss the key modeling parameters that influence the study results; document through sensitivity analysis the change in key impact categories that would alter the study conclusions, if applicable
4. Provide a summary narrative of the LCA study conclusions with recommendations to improve the accuracy and reduce the uncertainty of the results

# Critical Review

The U.S. DOE Carbon Utilization Program will serve as the critical reviewer for this study.

If additional critical reviews are conducted prior to submission to DOE, the names, affiliations, and contact information shall be documented for each external reviewer.

# References

# Appendix A: Supporting Information