

# CARBON DIOXIDE UTILIZATION LIFE CYCLE ANALYSIS GUIDANCE FOR THE U.S. DOE OFFICE OF FOSSIL ENERGY

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# ACRONYMS AND ABBREVIATIONS

BIC	Best-in-class	MJ	Megajoule
Btu	British thermal unit	MRO	Midwest Reliability Organization
CC	Carbon capture	MW	Megawatt
CH <sub>4</sub>	Methane	MWh	Megawatt-hour
CO <sub>2</sub>	Carbon dioxide	N <sub>2</sub> O	Nitrous oxide
CO <sub>2</sub> e	Carbon dioxide equivalent	NEMS	National Energy Modeling System
CO2U	Carbon dioxide utilization	NERC	North American Electric Reliability Corporation
DF	Documentation file	NETL	National Energy Technology Laboratory
DOE	Department of Energy	NGCC	Natural gas combined cycle
DS	Data summary	NO <sub>x</sub>	Nitrogen oxides
EIA	Energy Information Administration	NPCC	Northeast Power Coordinating Council
EIO	Economic input-output	NREL	National Renewable Energy Laboratory
EIOLCA	Economic input-output life cycle assessment	Pb	Lead
EOR	Enhanced oil recovery	PEF	Polyethylene furandicarboxylate
EPA	Environmental Protection Agency	PI	Principal investigator
EROI	Energy return on investment	PM	Particulate matter
FRCC	Florida Reliability Coordinating Council	R&D	Research and development
GHG	Greenhouse gas	RF	Reliability First
GWP	Global warming potential	SCPC	Supercritical pulverized coal
H <sub>2</sub> S	Hydrogen sulfide	SERC	SERC Reliability Corporation
HDPE	High-density polyethylene	SF <sub>6</sub>	Sulfur hexafluoride
IGCC	Integrated gasification combined cycle	SO <sub>2</sub>	Sulfur dioxide
ILCD	International Reference Life Cycle Data System	subPC	Subcritical pulverized coal
IPCC	Intergovernmental Panel on Climate Change	Texas RE	Texas Reliability Entity
ISO	International Organization for Standardization	tonne	Metric ton (1,000 kg)
kg	Kilogram	TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
km	Kilometer	U.S.	United States
kWh	Kilowatt-hour	VOC	Volatile organic compound
LCA	Life cycle analysis	WECC	Western Electricity Coordinating Council
LCI	Life cycle inventory	yr	Year
LNG	Liquefied natural gas		
MESA	Mission Execution and Strategic Analysis		

# GLOSSARY OF TERMS

The following includes the most common terms utilized in this document. For an extensive list of definitions, please see ISO 14040 and ISO 14044. All definitions that have been derived from ISO14040/14044 are cited accordingly. Glossary terms appear in italics the first time they are used in this document.

<b>Allocation</b>	“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” [1] [2]
<b>Best-in-class technology</b>	The method(s) of production for the CO2U process’s products in the Comparison Product System that represent the lowest GWP per unit product
<b>Characterization factor</b>	“factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator” [1] [2]
<b>Comparison Product System</b>	The entire life cycle boundary of the model that will be compared to the Proposed Product System for the CO2U project
<b>Comparison processes</b>	The systems in the Comparison Product System that produce equivalent functions to the system(s) in the Proposed Product System
<b>Contribution analysis</b>	LCA results delineated by unit process or life cycle stage
<b>Construction unit process</b>	A system that represents a one-time effort to create a discrete piece of equipment or infrastructure that will be used in an operational or transportation unit process, or another construction unit process
<b>Co-product</b>	One of the two or more products from a unit process or product system
<b>Co-product management</b>	Approach used to handle multiple products from a single product system – allocation and system expansion are example approaches
<b>Cradle-to-gate</b>	Unit process or life cycle boundary that includes resource extraction to production gate. Cradle to gate does not include end of life treatment
<b>Cradle-to-grave</b>	Unit process or life cycle boundary that includes resource extraction to end of life treatment
<b>Cut-off criteria</b>	“specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study” [1] [2]
<b>Displacement</b>	A co-product management method in which the system boundary is first expanded to include each co-product. The LCA model results are generated for all systems, the multi-functional unit is then reduced to one-product functional unit, by removing one unwanted product and related impacts at a time until only the desired product is left
<b>Elementary flows</b>	“Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation” [2]
<b>Emitters</b>	Producers within the CO2U supply chain that emit greenhouse gases
<b>Energy flow</b>	“Input to or output from a unit process or product system, quantified in energy units” [1] [2]
<b>Existing plant</b>	A power plant that has has been designed, construed, and is in operation prior to the temporal start period of the study
<b>Functional equivalency</b>	Two or more systems are defined to be in functional equivalency when it is determined that they yield the same functional unit
<b>Functional unit</b>	“quantified performance of a product system for use as a reference unit” [1] [2]
<b>GHG analysis</b>	An LCA that only considers one impact category: global warming potential
<b>Greenfield plant</b>	A new power plant that is designed without prior construction or site constraints. A greenfield plant in this document refers to a new power plant designed to redirect or capture the carbon dioxide from the flue gas for alternative use or geological sequestration
<b>Impact category</b>	“class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” [1] [2]
<b>Industry standard practice</b>	The method(s) of production for the CO2U process’s products in the Comparison Product System that represent the current, conventional method of production

<b>Input</b>	“Product, material or energy flow that enters a unit process” [1] [2]
<b>Intermediate flows</b>	“product, material or energy flow occurring between unit processes of the product system being studied” [1] [2]
<b>Long-run marginal</b>	Technology used to provide next MWh of electricity supply to the power grid in a given region
<b>Marginal-cost technology</b>	The method(s) of production that the CO2U process's products or functions will displace from the market on a cost-basis in the Comparison Product System
<b>Marginal capacity addition</b>	Forecasted addition of power generation technologies to the U.S. sector for a given year
<b>Midpoint impact category</b>	An impact assessment measure that uses environmental inventory data, but stops short of an assessment measure that goes all the way to the endpoint impact. For example, GHG emissions (e.g., CO <sub>2</sub> and CH <sub>4</sub> ) represents inventory data, CO <sub>2</sub> equivalent represents a midpoint impact, and radiative forcing represents an endpoint impact
<b>Multiproduct functional unit</b>	A functional unit with more than one function, as a result of using the system expansion co-product management method
<b>openLCA</b>	An open source LCA software available at <a href="http://openlca.org">openlca.org</a>
<b>Operational unit process</b>	A system that has continuous inputs and outputs to produce a mass or volume of product
<b>Output</b>	“Product, material or energy flow that leaves a unit process”
<b>Principal investigator</b>	A head researcher of a CO2U project under the U.S. DOE Carbon Utilization Program
<b>Producer</b>	The entity that has ownership or oversight over a process in a supply chain
<b>Product flow</b>	“products entering from or leaving to another product system” [1] [2]
<b>Product system</b>	“collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product” [1] [2]
<b>Properties</b>	Defining attributes of a product or service that help determine the appropriate functional unit assignment
<b>Proposed Product System</b>	The entire life cycle boundary for the CO2U project
<b>CO2U process</b>	The system within the Proposed Product System that includes the process under control by the principal investigator and produces the main co-product
<b>Reference flow</b>	“Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit” [2]
<b>Reference unit process</b>	The unit process in the system of connected unit process that everything in the system is scaled to.
<b>Retrofit plant</b>	An existing power plant that has been modified after its original design and start-up to include additional capabilities or services. A retrofit plant in this document refers to an existing power plant that has been modified to capture the carbon dioxide from the flue gas for alternative use
<b>Sensitivity analysis</b>	“systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study” [1] [2]
<b>System boundary</b>	“set of criteria specifying which unit processes are part of a product system” [1] [2]
<b>System expansion</b>	A co-product management method in which the boundaries of the LCA model are expanded to include all the co-products in the system
<b>Technosphere flow</b>	See Intermediate flows
<b>Tracked flow</b>	An unit process input or output flow that is designated for connection to another unit process
<b>Transportation unit process</b>	A systems that quantifies the impact of moving an input from one location to another
<b>Uncertainty analysis</b>	“systematic procedure to quantify the uncertainty introduced in the results of a life cycle inventory analysis due to the cumulative effects of model imprecision, input uncertainty and data variability” [1] [2]
<b>Unit process</b>	“The smallest element considered in the life cycle inventory analysis for which input and output data are quantified” [1] [2]

# 1.0 INTRODUCTION

Capturing carbon dioxide (CO<sub>2</sub>) and placing it in permanent storage in geologic formations is an option for reducing CO<sub>2</sub> emissions, but it may not be a viable one for all CO<sub>2</sub> emitters. For some, the added cost of capture may be too high to implement, or the geology near the source may not be suitable for storage. In these circumstances, other options will be needed. Carbon use and reuse, or CO<sub>2</sub> utilization (CO<sub>2</sub>U), is an alternative approach that seeks beneficial uses for captured CO<sub>2</sub>, such as using it as a feedstock in the production of fuels, chemicals, and building materials. These uses would give CO<sub>2</sub> value that could be used by suppliers (emitters) to offset capture costs.

One of the principal features and challenges associated with CO<sub>2</sub>U is that the products derived from CO<sub>2</sub> must have lower carbon footprints than their conventional counterparts. Previous assessments of CO<sub>2</sub>U alternatives have focused on the carbon content of utilization products as an indicator of CO<sub>2</sub> equivalent (CO<sub>2</sub>e) emissions reduction potential. However, embodied emissions are—at best—only weakly correlated with the amount of carbon contained in any physical product. Therefore, the most attractive CO<sub>2</sub>U options will both displace the carbon in an existing product and improve the overall carbon efficiency of the manufacturing process.

Research to overcome barriers will include identifying existing co-feeds and available low-carbon energy sources to enable the conversion of CO<sub>2</sub> to value-added products under favorable processing conditions. New discoveries in the fields of nano- and bio-technology will be applied to efficiently utilize CO<sub>2</sub> in new applications. Development of advanced materials and processes, integrating CO<sub>2</sub> capture with utilization processes (e.g., algae), exploring a diverse slate of products from CO<sub>2</sub> to effectively offset capture costs and developing processes based on waste energy are means to overcome these barriers. The research will lead to the development of advanced catalysts, materials, and equipment that can be used to convert CO<sub>2</sub> into useful products. The result will be multiple flexible and adaptable technology platforms that can be used to produce suites of products spanning multiple utilization pathways.

The United States (U.S.) Department of Energy (DOE), Office of Fossil Energy, National Energy Technology Laboratory (NETL) offers funding opportunities to principal investigators (PIs) developing CO<sub>2</sub>U technologies. The Funding Opportunity Announcement (FOA), *Applications for Technologies Directed at Utilizing Carbon Dioxide from Coal Fired Power Plants* (DEFOA-0001622), states that the PI shall provide:

“As part of the project, applicants selected under this FOA are required to supply DOE with all technical information described below, through the delivery of topical reports and a comprehensive final report...Life Cycle Analysis further demonstrating the potential of the proposed process to be a substantive CO<sub>2</sub> mitigation option, by verifying the lifecycle GHG reduction potential of the products(s) and technology (on a percent reduction basis) relative to current state-of-the-art pathways” [3]

Life cycle analysis (LCA) is an environmental assessment method for accounting for the environmental burdens from the extraction of raw materials from the earth to production and use of the product to perform a specific function for society. LCA is the analysis technique used by the U.S. DOE Carbon Utilization Program (formerly known as the “Carbon Use and Reuse Program”) to determine if a project will result in lower life cycle greenhouse gas emissions in terms of carbon dioxide equivalents (CO<sub>2</sub>e) than the current state-of-the-art option on the market. This knowledge is combined with economic and market performance data, technical risk evaluations, and other criteria to evaluate project merit.

## 1.1 INTRODUCTION TO LCA

Life cycle analysis (LCA) is a framework that assesses the comprehensive environmental impacts of a product or service over its lifetime. [1, 2] For the purposes of this document, the terms Life Cycle Analysis and Life Cycle Assessment shall be considered synonymous. LCA can be applied to a wide range of products and services, from the seemingly simple system of producing a paper bag to the large-scale generation of electricity. The life cycle of a product begins with raw material acquisition, includes production and use of a product, and ends with waste disposal and decommissioning activities. A comprehensive LCA is referred to as a *cradle-to-grave* LCA.

The following features distinguish LCA from other analytical platforms:

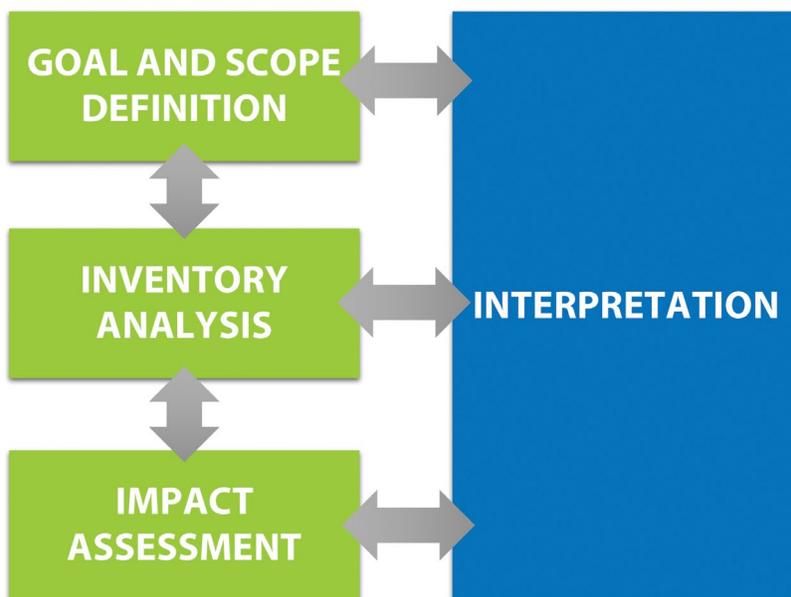
1. Depth and breadth of environmental impacts considered
2. Connectivity between processes
3. Comparability across systems
4. Standardized approach developed by the International Organization for Standardization (ISO)

LCA has broad application potential from research and development (R&D) to policy. Researchers can use LCA to identify key sources of environmental burdens in a system, thereby justifying focused research efforts. Policy makers can use LCA to evaluate the potential consequences of national-level energy policies. LCA can be combined with other analytical approaches to identify trade-offs between environmental and economic performance of systems.

LCA consists of four phases as illustrated in **Exhibit 1-1**:

1. **Goal and Scope:** Defined based on the question being asked of the analysis – “depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA” [1, 2]
2. **LCI – Life Cycle Inventory:** Detailed accounting for the *input* and *output* flows for a process or product, includes the necessary data collection to populate the system of study as defined by the goal and scope of the analysis
3. **LCIA – Life Cycle Impact Assessment:** Characterization of environmental, resource, and health impacts using the LCI
4. **Interpretation:** Development of summary and conclusions of the study based on the results of the LCI/LCIA

EXHIBIT 1-1. LCA FRAMEWORK (ADAPTED FROM [2])



The principles of LCA and requirements for conducting a study have been codified in two standards by the International Organization for Standardization (ISO):

1. **ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework:** ISO 14040 describes the “principles and framework for LCA.” Specifically it “covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.” [1]
2. **ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines:** ISO 14044 specifies requirements and provides guidelines for LCA. [2]

## 1.2 DOCUMENT GOALS

All of the guidance included herein complies with the ISO LCA standards (14040/14044). Additional guidance is helpful for handling CO2U systems for the following reasons:

1. Ensure methodological consistency in applying the ISO standards - ISO standards provide a broad framework for applying LCA to a wide range of applications. This can lead to inconsistency in modeling choices and results interpretation that can confound or negate study conclusions.
2. Define study goal & scope based on project Technology Readiness Level (TRL) - There can be a lot of unknowns in the life cycles of emerging technologies. This guidance aims to assist principal investigators with the expectations of completing their comparative LCAs at different stages of technology development.

The goals of the NETL CO2U Guidance Toolkit are as follows:

1. Provide LCA guidance, data, and tools to U.S. DOE Carbon Utilization Program project PIs to complete their project LCA and documentation requirements,
2. Foster better decision-making for the Carbon Utilization Program by providing an analysis and reporting structure for the project LCAs that allows for consistency and transparency,
3. Provide LCA guidance, data, and tools to others seeking guidance on conducting LCA in the area of CO2U, and
4. Contribute to the global discussion on CO2U LCA and LCA methods.

## 1.3 WHAT IS INCLUDED IN THE NETL CO2U LCA GUIDANCE TOOLKIT

The **NETL CO2U LCA Guidance Toolkit** includes the following:

1. **NETL CO2U LCA Guidance Document** (this document) outlines the analysis requirements and how to use the supporting data and tools
2. **NETL CO2U openLCA LCI Database** is an openLCA database that includes NETL unit process data and an example CO2U LCA
3. **NETL CO2U openLCA Results Contribution Tool** is an Excel template that translates openLCA results into required charts
4. **NETL CO2U LCA Documentation Spreadsheet** is an Excel file that can be used to document data when not using openLCA
5. **NETL CO2U LCA Report Template** is a Word report template for summarizing data and results
6. **NETL CO2U openLCA Model Training Resources** will be provided to PIs to aid in the implementation of their LCA in the openLCA modeling platform
7. **NETL CO2U LCA Subject Matter Expert Support** will be available to PIs as they work through all phases of the LCA from conception to documentation.

## 1.4 HOW TO USE THIS DOCUMENT AND TOOLKIT

The **NETL CO2U LCA Guidance Toolkit** is designed to provide requirements and assistance to PIs as they complete an LCA of their project as required by the U.S. DOE Carbon Utilization Program.

This document is meant as a supplement to, not a replacement for, the ISO LCA standards (14040/14044). ISO 14040/14044 are necessarily general so as to apply to any potential product or system and thus, this document endeavors to provide specific requirements necessary to complete an LCA as required by the U.S. DOE Carbon Utilization Program.

Requirements are denoted by the use of the word ‘shall.’ Recommendations are denoted by the use of the word ‘should.’

This document is designed for PIs that have basic knowledge of the LCA method according to the International Standards Organization (ISO) standards for LCA, ISO 14040 and 14044. [1, 2]

The sections of the document should be used in the following ways:

- **Section 2** provides more specific guidance on the LCA method that U.S. DOE Carbon Utilization Program project PIs must use to produce their LCAs.
- **Section 3** provides guidance on using the **NETL CO2U openLCA LCI Database** to produce an LCA with expanded inventory for the U.S. DOE Carbon Utilization Program.
- **Section 4** provides guidance on using the **NETL CO2U openLCA Results Contribution Tool** to translate openLCA results into required charts.
- **Section 5** provides guidance on using the **NETL CO2U LCA LCA Documentation Spreadsheet** to provide documentation for the U.S. DOE Carbon Utilization Program, mainly when not using openLCA.
- **Section 6** provides guidance on what to include in the **NETL CO2U LCA Report Template**.

- **Appendix A** provides instructions for accessing the components of the CO2U LCA Toolkit and resources for assistance with completing the required LCA including the **NETL CO2U openLCA Model Training Resources** and **NETL CO2U LCA Subject Matter Expert Support**.
- **Appendix B** provides background on U.S. DOE's technology readiness levels (TRLs) referred to in this document.
- **Appendix C** describes alternative coproduct management methods for PIs wanting to generate additional results that do not use *system expansion*.
- **Appendix D** provides supporting information for NETL's calculation of energy capacity and consumption mixes **Section 2.1.5**.
- **Appendix E** lists the NETL unit processes provided in the **NETL CO2U openLCA LCI Database** and the **NETL CO2U LCA Documentation Spreadsheet**.
- **Appendix F** provides additional guidance on reading the **NETL CO2U openLCA Results Contribution Tool** generated graphs.

## 1.5 MODELING AND DOCUMENTATION OPTIONS FOR U.S. DOE CARBON UTILIZATION PROGRAM PROJECT PIS

U.S. DOE Carbon Utilization Program project PIs may model their LCA in one of three ways. The following establishes the reporting requirements depending on this choice:

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

## 2.0 OVERVIEW OF THE LCA STEPS AND METHODS REQUIRED FOR U.S. DOE CARBON UTILIZATION PROGRAM PROJECTS

This section follows the four phases of LCA as defined in **Exhibit 1-1**. Each section provides the necessary background and the requirements established by the U.S. DOE Carbon Utilization Program.

### 2.1 GOAL AND SCOPE DEFINITION

The goal of an LCA as defined by ISO 14040 requires statement of the intended application, the reasons for carrying out the study, the intended audience, and whether or not the results are intended to be used in comparative assertions that will be disclosed to the public [2].

The scope of an LCA must include considerations for the following (adapted from [2]):

1. Product system to be studied
2. System functional and functional unit
3. System boundary
4. Allocation procedures
5. Impact categories selected and methodology of impact assessment
6. Data Representativeness

Each is described below in the following sections.

#### 2.1.1 U.S. DOE CARBON UTILIZATION PROGRAM LCA STUDY GOAL

The specific goals of the LCA as required by this document are described below:

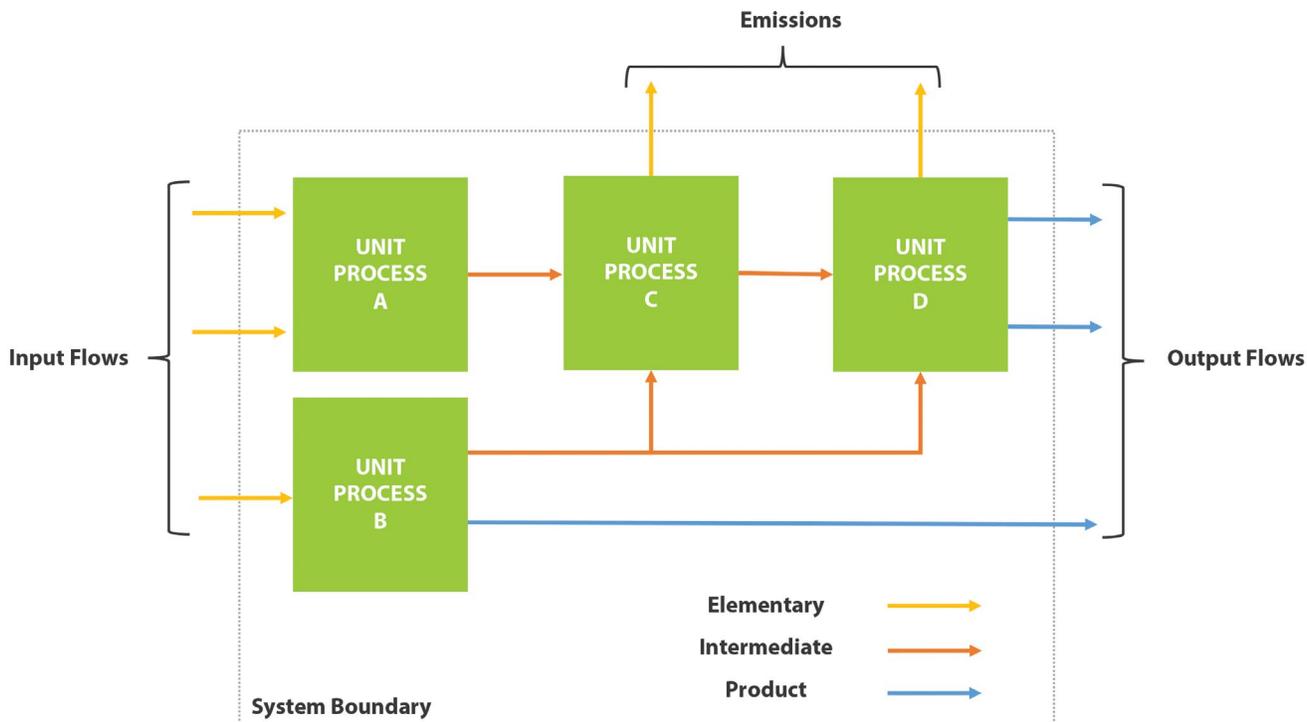
1. Intended application - The intended application of the LCA produced by U.S. DOE Carbon Utilization Program project PIs is to compare the life cycle GHG impact of their project, as part of a *Proposed Product System*, to a *Comparison Product System*. The Proposed Product System is based on the PIs project. See **Section 2.1.3.2** for more on determining the Comparison Product System.
2. Reasons for carrying out the study - to understand how the environmental impact of the CO2U technology life cycle compares to the life cycle of a system that produces the same products.
3. Intended audience - The intended audience for LCA described herein is the U.S. DOE Carbon Utilization Program.
4. Public disclosure – The LCAs conducted as part of the FOA requirement will become part of the public record for the award within the *Final Scientific/Technical Report*.

#### 2.1.2 PRODUCT SYSTEM DESCRIPTION

The product system of study is defined as the collection of “processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.” [2] An example product system is depicted in **Exhibit 2-1**.

For the purposes of this guidance, the product system of interest, which includes a CO2U process, is referred to herein as the Proposed Product System. The Comparison Product System produces the same products as the Proposed Product System using a feedstock other than CO<sub>2</sub>.

EXHIBIT 2-1. EXAMPLE OF AN LCA PRODUCT SYSTEM



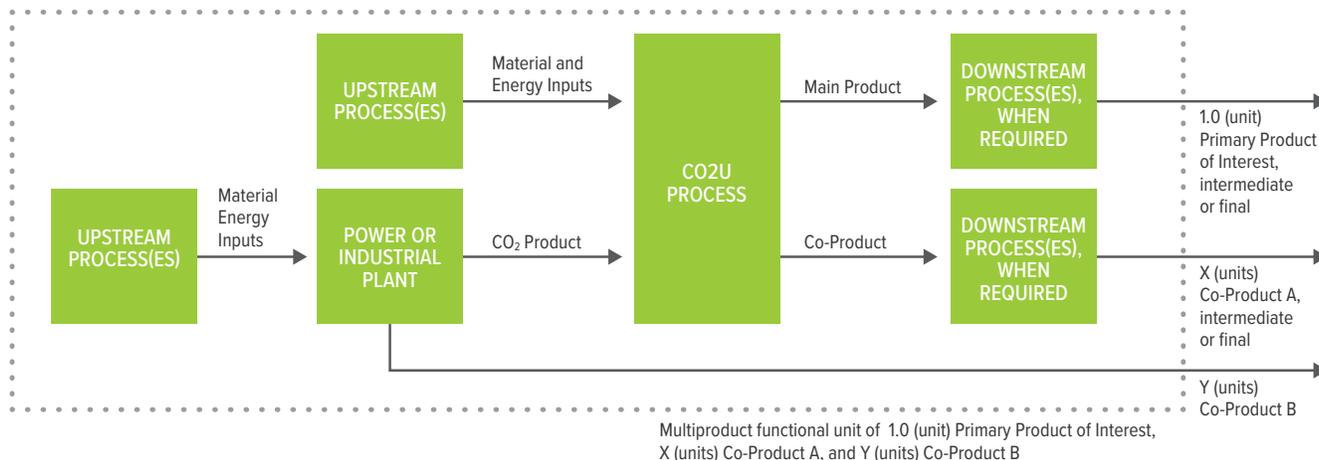
### 2.1.3 FUNCTIONAL UNIT OF THE STUDY

One of the primary purposes of LCA is to compare one alternative to another. Thus, a fair and standard basis of comparison must be established in the beginning stages of an LCA. This basis of comparison is the functional unit. The functional unit shall include all of the services and/or functions being provided by the products exiting the system boundary. The functional unit may have one or more products exiting the system boundary. Most, if not all, CO2U projects will have more than one output flow leaving the system boundary, this is referred to as a multiproduct functional unit.

#### 2.1.3.1 PROPOSED PRODUCT SYSTEM

The multiproduct functional unit for the LCA, that will be conducted per this guidance, will include the product(s) of the CO2U process and the electricity that is associated with the source of CO<sub>2</sub> that is utilized by the CO2U process. If the CO2U process yields multiple products, they will also become part of the multiproduct functional unit. For example, 1 unit of the primary product of interest plus X units of co-product A plus Y units of co-product B (see Exhibit 2-2).

EXHIBIT 2-2. PROPOSED PRODUCT SYSTEM



A life cycle model scales the inputs and outputs of all unit processes to the primary function in the multiproduct functional unit. In the case of the previous example, that would mean that the model scales to 1 kg of product A. This is why the other products in the example are denoted as X and Y; their final quantities are not yet known.

The multiproduct functional unit comprises all product flows, functions, and/or services provided by the system under study. The multiproduct functional unit describes both the flows (magnitude) and defining *properties* of products and services provided by the system under study. In this context, properties describe both the underlying physical relations (mass, energy, volume) and other defining attributes (functionality, technical quality, etc.) of products and services, and may be driven by requirements in the market for which the product or service is sold. Properties may include but are not limited to:

- **Functionality**, related to the primary function of the product or service (e.g., “drop-in replacement fuel,” “baseload power”)
- **Technical quality**, including but not limited to the material properties, stability, ease of maintenance, and durability (e.g., “tensile strength of biopolymer,” “octane rating,” “energy density”)
- **Other defining attributes** (e.g., environmental properties, market value, energy quality)

The Pls shall adhere to the following protocol for determining the multiproduct functional unit for the U.S. DOE Carbon Utilization Program CO2U LCA:

1. Itemize all product and service flows encapsulated within the system boundary, include flow description and magnitude.
2. Describe the defining properties of each product or service flows itemized in step 1:
  - a. Defining properties include but are not limited to obligatory product properties or statutes required by the market/industry.
  - b. When possible chose a function-based perspective, i.e., based on the value or critical functions fulfilled by the products (e.g., “X megawatt-hour (MWh) of baseload power delivered” and “Y megajoule (MJ) of drop in replacement fuel”) rather than solely based on the physical products themselves (e.g., “X MWh of electricity” and “Z kg of renewable diesel”).
3. Assign a “long” functional unit name that includes all of the defining properties and a “short” functional unit name that summarizes the function and can be used as shorthand in the analysis.
4. Note which of the products from the Proposed Product System is the main product to which the LCA will scale.

There are several examples that can be described in more detail that illustrate the challenge in defining an appropriate functional unit for a given product or service. For product LCAs, a functional unit could be one unit of the product, but that is not always the best representation of the service provided to society to enable a fair comparison. For example, the function of a household cleaner is to clean a surface, so the amount of cleaner required to clean a specific surface size would be a fair basis of comparison between two cleaners, because some cleaners may be less concentrated than others and require more of the product to perform at a comparable level. Another example may be two t-shirts made of different fabrics, with one lasting longer than the other. In this case, the t-shirt with the longest lifetime could be used to create a fair comparison. So, if it takes 2.5 of t-shirt B to reach the lifetime of t-shirt A, the functional unit is the number of t-shirts per lifetime of t-shirt A (one t-shirt A and 2.5 t-shirt B).

In the case of a *cradle-to-gate* function, a plastic resin that is sold to make a myriad of products has a function that is based on its properties. This could be as simple as the type of plastic resin that it is, such as high-density polyethylene (HDPE), but it could also include other properties, if it is not identical to all HDPE resins. The form of the resin may also be relevant (e.g., pellets, granules, or powders), which could affect the kind of downstream processing that can be applied to the resin.

There is also the case of specialized products that may, for example, intend to provide multiple functions. For example, a premium animal feed or fortified product that is intended to ultimately provide a final food product to the consumer that includes more nutrients than the standard production of that product. In this case, the product provides the standard function (e.g., calories or protein), but also an additional function of added nutrients (e.g., vitamin D or omega fatty acids). This will then inform how the Comparison Product System is developed, perhaps resulting in the need for two products to achieve the same function in the Comparison Product System (e.g., the standard food item plus a vitamin supplement). See **Section 2.1.4** for more information on determining a Comparison Product System.

**Exhibit 2-3** provides a table that illustrates some example functional units that are relevant to CO2U projects. This table is not meant to provide examples of fully explored defining properties, but rather to show the differences between cradle-to-gate and cradle-to-grave functional units. See **Section 2.1.4** to understand when it is acceptable to use an intermediate functional unit versus final functional unit.

EXHIBIT 2-3. EXAMPLE OF POTENTIAL FUNCTIONAL UNITS FOR VARIOUS MAIN PRODUCTS

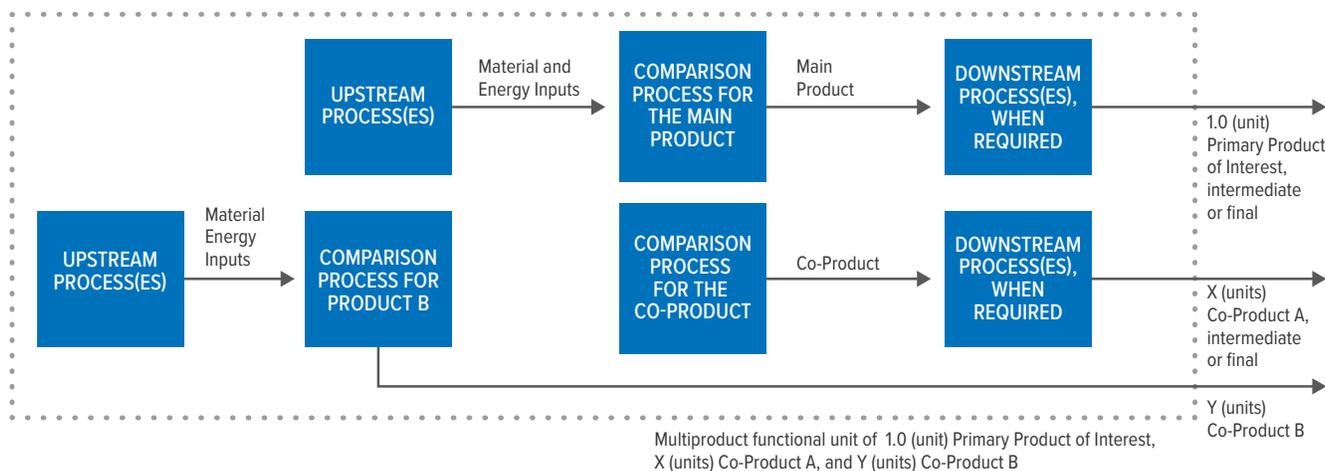
CO2U PROCESS EXAMPLE		FUNCTIONAL UNIT EXAMPLES	
Main Product of the Proposed Process	Cradle to Gate <-----> Cradle to Grave		
Algal biodiesel	1 MJ drop-in diesel fuel	1 MJ drop-in diesel fuel combusted in a diesel engine	1 km vehicle travel
Bioplastic resin	1 kg HDPE resin pellets	1 durable plastic product A	20 years of durable plastic product A use
Mineralized railroad ties	1 railroad tie (size, durability, and strength/compressibility)		1 km railroad construction, operation, and maintenance over 40 years
Formic acid	1 kg formic acid	1 kg solvent	1 application of solvent product X as directed on product label

2.1.3.2 COMPARISON PRODUCT SYSTEM

Once the function of the Proposed Product System is defined, the Comparison Product System and constituent unit processes can be determined to yield *functional equivalency*.

The CO2U processes is the system that is under control of the Pls. The *comparison processes* produces the same product or service for each function but using a different technology or technologies than the proposed process. If a CO2U process has multiple co-products (functions), there will be a comparison process for each co-product. Note that “CO2U process” and “comparison process” is different from “Proposed Product System” and “Comparison Product System” in this document. Proposed Product System and Comparison Product System include the entire life cycle boundaries, while CO2U process is limited to the unit processes that contain the main co-product of the LCA. The comparison processes are the unit processes that produce the same co-products as the Proposed Product System. Therefore, the CO2U process resides within the Proposed Product System and the comparison process resides within the Comparison Product System (see **Exhibit 2-4**).

EXHIBIT 2-4. COMPARISON PRODUCT SYSTEM



There are likely multiple technologies that can produce a product or function from the Proposed Product System. Pls with project TRLs of 5 or higher shall use marginal-cost technologies for the comparison processes. Pls with project TRLs of 1-4 shall use the following hierarchy for determining the type of technology for inclusion in the Comparison Product System to ensure functional equivalence. This hierarchy shall be considered for each of the products/services produced in the Proposed Product System.

- Marginal-cost technology:** Choose the method of production that the CO2U process product or service will displace from the market on a cost-basis. If sufficient data<sup>a</sup> is not available to determine the *marginal-cost technologies* for the comparison process, then identify the best-in-class (BIC) technology.
- Best-in-class (BIC) technology (GHG-performance):** Identify the method of production for the CO2U process product or service that represents BIC GHG performance (i.e., lowest GWP per unit product). If sufficient data is not available to determine the BIC technology for the comparison process, then identify the *industry standard practice technology*.

<sup>a</sup> Data refers to LCI data from LCI databases, scientific literature, or industry reports.

3. **Industry standard practice technology:** Identify the method of production for the CO<sub>2</sub>U process product or service that represents standard industry practices for production.
4. Repeat this hierarchy until comparison technologies have been identified for all of the products/services from the Proposed Product System.

Note that additional guidance on selecting the marginal-cost technology for the comparison process for the electricity co-product generated by the coal power plant that produces the CO<sub>2</sub> product in the Proposed Product System is provided in **Section 2.1.5**.

### 2.1.4 SYSTEM BOUNDARY

A complete LCA is a cradle-to-grave analysis, with a boundary that begins with the extraction of raw materials and ends with the consumption or disposal of the final product (*end of life*). In some instances, a partial LCA that calculates cradle-to-gate results is appropriate if functional equivalency between the Proposed Product System and Comparison Product System can be determined without modeling the complete life cycle. This is acceptable within this guidance with proper justification of functional equivalency. However, partial LCA results should be used with care because they do not represent a complete life cycle perspective.

Establishment of functional equivalency between the Proposed Product System and Comparison Product System at an intermediate point in the life cycle and alignment with the goals of a study are reasons for using a cradle-to-gate analysis. For example, in the case of a CO<sub>2</sub>U process that produces intermediate chemicals,<sup>b</sup> the final product made from the intermediate chemicals may not yet be known. In this case, conducting a cradle-to-grave LCA would require accounting for all possible final products as well as the likelihood of manufacture in comparison to one another. A weighted LCA accounting for the suite of final products could be an option. This could potentially become a cumbersome or near impossible activity due to knowledge gaps. If the Pls do not know what a final product will be and cannot characterize the suite of options due to knowledge gaps or future market uncertainty, the Pls may truncate at the intermediate level for the product/function in question. When truncating the system boundary of the study, it is critical that only processes that follow after the point of functional equivalence is reached be considered for truncation. All processes, even if similar, in the system boundary prior to the point of functional equivalency must be included in both the Proposed and Comparison Product System boundaries.

For instance, the Pls may find that when they draw the complete boundaries for the Proposed Product System and Comparison Product System, that there are portions of the life cycle where the two product systems use identical unit processes with identical input and output quantities. For example, if a CO<sub>2</sub>U process makes plastic resin that is turned into a product and the Comparison Product System makes the exact same plastic resin that is turned into the same product, the processes downstream of resin production will be identical. In these cases, the Pls can exclude the downstream unit processes from the life cycle, because, mathematically, the results would cancel each other out in the comparison. However, this cannot be done if the unit processes are connected to downstream unit processes that are not identical. Additionally, if the unit process being considered for exclusion is the unit process that creates the functional unit, then the functional unit will need to be changed as well and the new functional unit must be valid. The drawback of truncating the life cycle is that the ratio of the calculated difference between the two product systems changes, because the total has changed, directly impacting the interpretation and utility of the results.

For the purposes of this guidance document for the U.S. DOE Carbon Utilization Program, the key metric is “a life cycle GHG reduction potential of the products(s) and technology (on a percentage reduction basis) relative to current state-of-the-art pathways.” Because this metric does not require a stated percent reduction in life cycle GHG emissions (e.g., 10% lower than the state-of-the-art pathways) and only a better-or-worse-than decision reported in terms of a percent reduction basis, truncation of the system boundary is acceptable.

The Pls shall illustrate Proposed Product System and the Comparison Product System diagrams based on the goals and scope (**Section 2.1**) of the LCA study while ensuring equivalent functions are provided by both product systems. These diagrams will inform the direction of research for data development and life cycle boundary development. Quantities of inputs and outputs may or may not be known at this stage. If either the Proposed Product System or the Comparison Product System includes an input that is a waste product, the alternative fate of that waste product needs to be included in the other product system. For example, if mining waste is an input in the Proposed Product System for making mineralized building products, the Comparison Product System needs to include the alternative fate of the mining waste such as the impacts of disposal of that waste.

The Pls shall illustrate the final system boundary of the Proposed Product System and the Comparison Product System based on any changes that have occurred during data development. For example, there may be additional parts of the life cycle to show or additional co-products/functions to include. openLCA can be used to create the product system diagram automatically or alternative software can be used to manually create the product system diagrams.

<sup>b</sup> Intermediate chemicals are chemicals that are not final chemicals for consumer use and must undergo further processing or are used as an input to another process to make a marketable product that provides a service to society.

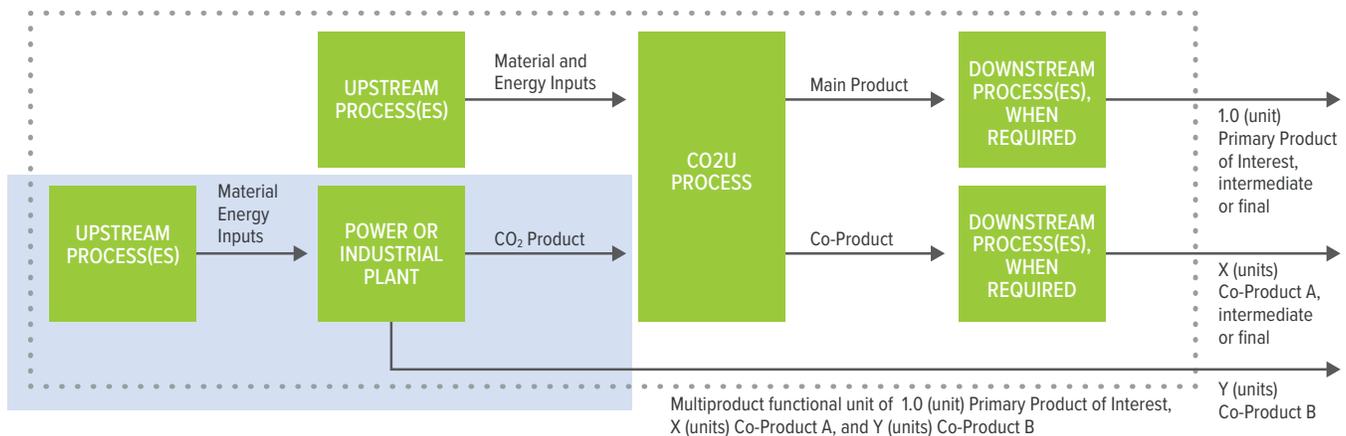
Note that product system diagrams are schematics of the relevant supply chains inclusive of both operations and construction thereof. For instance, unit process flow diagrams often include *construction unit processes* that feed into *operational unit processes*.

## 2.1.5 CARBON DIOXIDE SOURCE

The upstream CO<sub>2</sub> source choice affects the analysis results. CO<sub>2</sub> can be sourced from flue gas or captured CO<sub>2</sub>, from *greenfield plants* or *existing plants*, and from power or industrial sources. This influences the goal and scope of the study that guides the Comparison Product System and other study design choices strongly.

Based on the modeling framework established within these guidelines, all U.S. DOE Carbon Use and Reuse CO2U projects will have a minimum of two products exiting the system boundary. This is because the source of the CO<sub>2</sub> material input into the CO2U project (i.e., coal-fired power plant)<sup>c</sup> is included within the system boundary and that source co-produces electricity and CO<sub>2</sub> as products (*technosphere flows*). Therefore, Pls shall model the Proposed Product System with the CO<sub>2</sub> source coming from a coal-fired power plant with an electricity co-product (see blue highlighted section of **Exhibit 2-5**). Pls may create alternative product systems with other upstream CO<sub>2</sub> sources and co-products. A written justification shall be provided for each additional product system describing its purpose and preference if deemed more relevant than the required NETL coal-fired power plant scenario by the Pls. The following carbon dioxide specifications shall be used if no site-specific conditions exist: NETL Quality Guideline for Energy System Studies: CO<sub>2</sub> Impurity Design Parameters, NETL/DOE-341/011212. [5]

**EXHIBIT 2-5. PROPOSED PRODUCT SYSTEM WITH CO<sub>2</sub> FROM COAL POWER PLANT**



Understanding where anthropogenic CO<sub>2</sub> is obtained from and in what form is necessary to determine the appropriate comparison process for the electricity co-product. With respect to coal-fired power plants, there are several defining characteristics that need to be determined as shown in **Exhibit 2-6**: (a) Flue gas or (b) Captured CO<sub>2</sub>. Within each of these options, a number of different configurations can be analyzed, depending on the system in place. Regardless of the state in which the CO<sub>2</sub> is received (i.e., dilute (flue gas) or compressed and concentrated (captured)), choices must be made as to the type of facility from which it originates. For flue gas, the source of CO<sub>2</sub> can be a greenfield plant or an existing plant. For the purposes of this document, it is assumed that the greenfield plant would use supercritical pulverized coal (SCPC) technology and the existing plant would employ subcritical pulverized coal (SubPC) technology. For captured CO<sub>2</sub>, the same options exist, except the existing plant is referred to as a *retrofit plant* since it has been equipped with carbon capture technology after its original construction and commissioning. Specific guidance is provided below for each of the potential options.

Only one option (as depicted in **Exhibit 2-6**) is required to be modeled as the default NETL CO<sub>2</sub> source. The choice will depend on the CO2U project's CO<sub>2</sub> input requirements, site-specific requirements and technical requirements. The Pls shall document the justification for the selection of CO<sub>2</sub> source in the goal and scope of the LCA report. If only the choice of diverted (dilute) flue gas or captured (concentrated) flue gas is known at the time of conducting the LCA, then the "Greenfield Plant" option shall be selected for comparative analysis.

Depending on the maturity of the project of study, the exact source of CO<sub>2</sub> may or may not be known. **Exhibit 2-7** provides guidance on which scenarios to model depending on the answer to the following question—is the specific source of CO<sub>2</sub> known? Finally, **Exhibit 2-8** includes a summary of the guidance for the various options described in this section.

<sup>c</sup> This guidance is specific to the use of CO<sub>2</sub> obtained from a coal-fired power plant. The methodology and application can be applied to other sources of anthropogenic CO<sub>2</sub> obtained for use as a material input to a CO2U project.

EXHIBIT 2-6. POSSIBLE ELECTRICITY CO-PRODUCT OPTIONS BASED ON SOURCE OF CO<sub>2</sub>

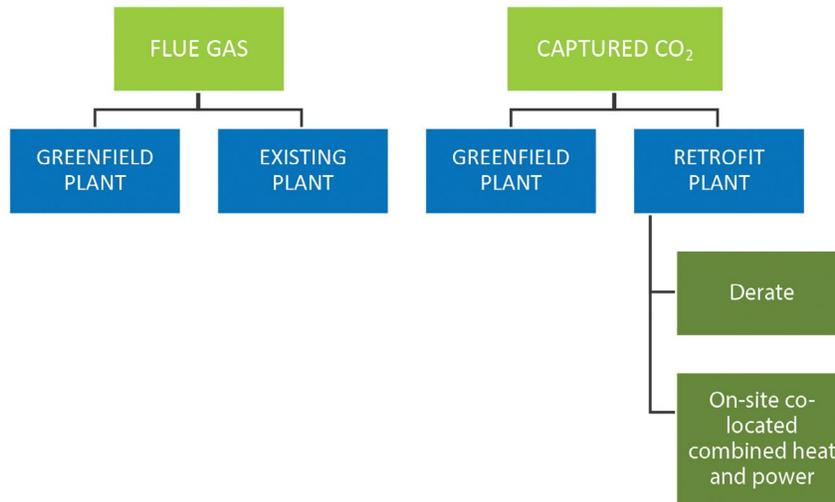


EXHIBIT 2-7. MODEL DESIGN REQUIREMENTS FOR SOURCE OF CO<sub>2</sub>

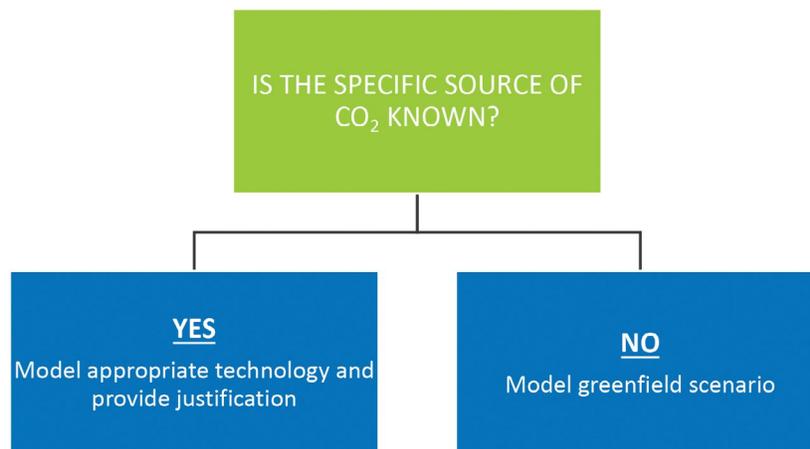


EXHIBIT 2-8. SUMMARY OF PROPOSED GUIDELINES FOR CONSIDERING ELECTRICITY CO-PRODUCT BASED ON TYPE OF CO<sub>2</sub> INPUT TO THE CO2U PROJECT

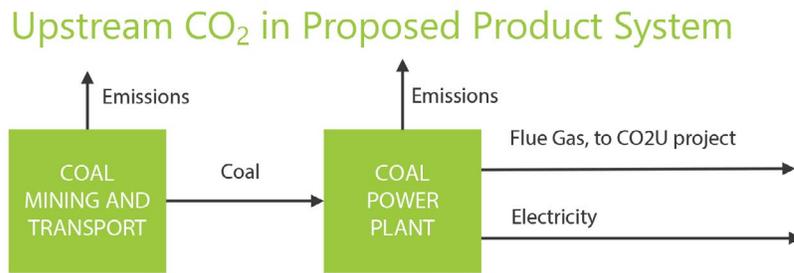
CO <sub>2</sub> STREAM TYPE	PLANT TYPE	PROPOSED PRODUCT SYSTEM	COMPARISON PRODUCT SYSTEM
<b>Flue Gas</b>	Existing or greenfield	Same power plant with flue gas diversion	Power plant with no flue gas diversion
<b>Captured CO<sub>2</sub></b>	Greenfield (SCPC)	New coal power plant with CO <sub>2</sub> capture	Mix of technologies from capacity expansion model corresponding to year of deployment
	Retrofit with de-rate (SubPC)	Same power plant with CO <sub>2</sub> capture producing less electricity due to de-rate; include addition of electricity generation mix to match output from Comparison Product System using data from <b>Appendix D</b>	Power plant with no CO <sub>2</sub> capture
	Retrofit with no de-rate (SubPC)	Same power plant with CO <sub>2</sub> capture	Power plant with no CO <sub>2</sub> capture; addition of electricity generation mix to match output from Proposed Product System using data from <b>Appendix D</b>

\* Note: If the CO2U project has established a contractual relationship with a coal-fired power plant CO<sub>2</sub> provider, the plant-specific performance characterization shall be modeled as an alternative product system recommended as the comparison system for project evaluation. The NETL default model design shall still continue to be included in the LCA study as the primary product system for comparison.

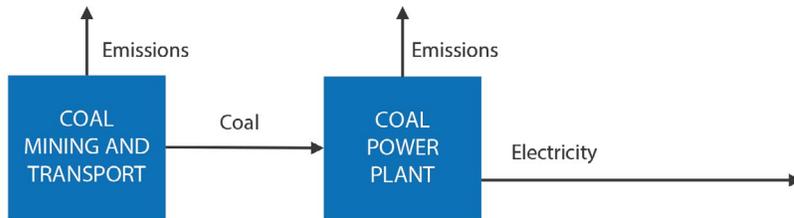
### 2.1.5.1 FLUE GAS DIVERSION OPTION

In the case where flue gas from a power plant is diverted for downstream utilization, no large-scale changes to the power plant occur and it will continue to produce the same amount of electricity, at the same production cost. (Therefore, its behavior in the electricity market remains unchanged.) Both the greenfield plant and existing plant options for flue gas diversion are modeled and compared in the same manner when applying system expansion within the LCA modeling approach.<sup>d</sup> The Proposed Product System shall include a power plant with flue gas diversion, while the Comparison Product System shall contain the same power plant without flue gas diversion (see **Exhibit 2-9**). Any energy requirements required for preprocessing the flue gas stream (e.g., impurity removal) for the CO<sub>2</sub>U process shall be considered only in the Proposed Product System as part of the CO<sub>2</sub>U project using average energy profiles representative of the specified geographical region. If the CO<sub>2</sub>U project includes the capital and operating expenses for providing on-site electricity generation and preprocessing of the flue gas stream physically occurs at the CO<sub>2</sub>U project location, the energy profile of the CO<sub>2</sub>U project's on-site electricity generation source shall be used to represent the proposed CO<sub>2</sub>U project design.

**EXHIBIT 2-9. ELECTRICITY SUB-SYSTEM FOR CO<sub>2</sub> FROM FLUE GAS**



### Electricity Co-product in Comparison Product System



### 2.1.5.2 CAPTURED CO<sub>2</sub> OPTIONS

The captured CO<sub>2</sub> option in **Exhibit 2-6** includes three unique sub-options that require different treatment while analyzing life cycle emissions. This includes two scenarios where CO<sub>2</sub> is separated from the flue gas stream and compressed by retrofitting an existing plant with necessary technology after the point of initial construction and commissioning (i.e., retrofit plant), and a third scenario where CO<sub>2</sub> capture and compression are designed and installed prior to the commissioning of the new coal-fired power plant (i.e., greenfield plant). The amount of electricity that must be accounted for as a co-product in captured CO<sub>2</sub> scenarios depends on the generation technology as shown in **Exhibit 2-10**.

**EXHIBIT 2-10: ELECTRICITY GENERATED PER UNIT OF CO<sub>2</sub> CAPTURED**

POWER PLANT TYPE	ELECTRICITY CO-PRODUCT (kWh/kg CO <sub>2</sub> )
SCPC	1.14
SubPC	1.10

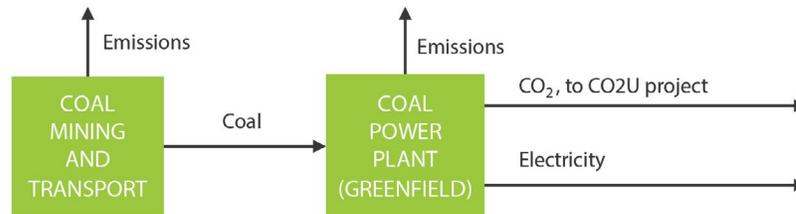
<sup>d</sup> System expansion LCA modeling approach minimizes the importance of determining if the diverted flue gas should be classified, from an LCA modeling perspective, as an environmental flow (i.e., waste stream) or technosphere flow (i.e., intermediate material or energy flow within the system boundary). Within this guidance document, any waste stream that is diverted and managed for use as a material or energy input to intentionally produce a marketable product, independent of its economic value, is classified and managed as a technosphere flow. Waste treatment operations that are intentionally designed to reduce or improve the management of a waste stream prior to final disposition in the environment or engineered system (e.g., landfill, wastewater treatment system) may also produce a marketable product (e.g., landfill gas, digester gas) that exists they LCA system boundary as a co-product. These co-products should also be managed as technosphere flows in accordance with the system expansion guidelines outlined in this document for comparative assessments.

## Comparison Product System Definition for CO<sub>2</sub> Sourced from a Greenfield Power Plant Equipped with Carbon Capture Technology

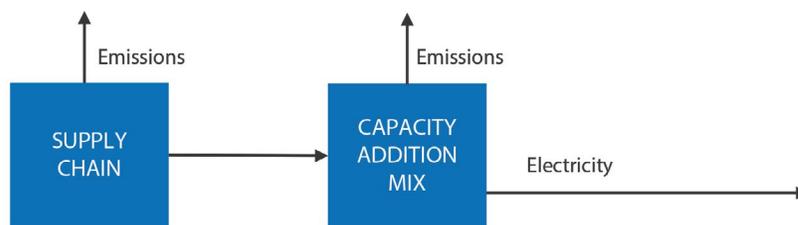
In the scenario where a new power plant with carbon capture technology is built that provides CO<sub>2</sub> for utilization, it is important to understand if the power plant would have been built in the Comparison Product System, and if not, what would have otherwise been built in its place (see **Exhibit 2-11**). Therefore, it is necessary to determine the *long-run marginal* cost alternative(s) that would have been selected by the market as capacity additions if the Proposed Product System did not result in the commissioning of the greenfield power plant equipped with carbon capture technology. This approach is modeling the consequences of the decision to implement the proposed CO<sub>2</sub>U project. The following describes how to determine the long-run marginal cost alternative of large-scale electricity capacity additions in the United States.

### EXHIBIT 2-11. ELECTRICITY SUB-SYSTEM FOR CAPTURED CO<sub>2</sub> FROM GREENFIELD POWER PLANT

#### Upstream CO<sub>2</sub> in Proposed Product System



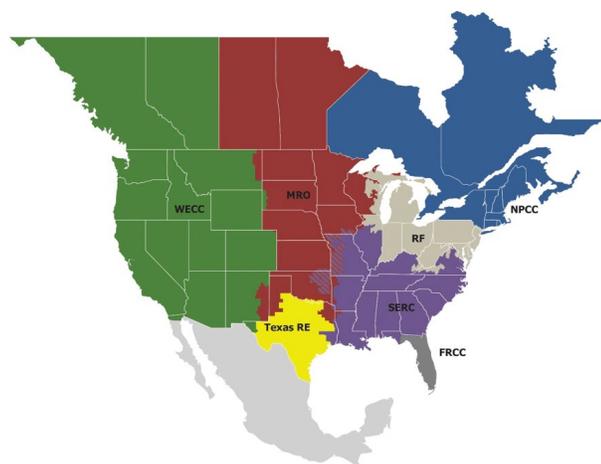
#### Electricity Co-product in Comparison Product System



Capacity expansion models are typically used to develop projections of future electric capacity and transmission. Similar estimates are developed in large-scale energy economic models (that use lower-resolution representations of the power sector), for example, the U.S. Energy Information Administration's (EIA) National Energy Modeling System (NEMS). If a new coal plant with carbon capture technology (to provide CO<sub>2</sub> for utilization) were to be built instead, some capacity additions in the Comparison Product System would likely be avoided/displaced. To generalize, the Comparison Product System shall be informed by projections from existing capacity expansion models or energy-economic models, for the proposed deployment year in the future (e.g., 2025). In the Proposed Product System, a new coal plant with capture would be included in the power system, but some power plants would be excluded, as determined by cost-optimal solutions.

Without specific knowledge of the exact technology replacement (e.g., coal with carbon capture technology displaces a similar-sized facility of some technology), it is recommended that the Comparison Product System represent a weighted mix of technology capacity additions expected to be deployed in the year of study. LCI data for the Comparison Product System electricity product is based on the 2019 EIA Annual Energy Outlook Reference Case capacity expansion scenario.[6] Those data are provided in the accompanying **NETL CO<sub>2</sub>U openLCA LCI Database** in five-year increments by North American Electric Reliability Corporation (NERC) region. See **Exhibit 2-12** for a map and list of the NERC regions.

EXHIBIT 2-12. NERC REGION MAP\* [3]



NERC REGION ACRONYM	NERC REGION NAME
FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	Reliability First
SERC	SERC Reliability Corporation
SPP	Southwest Power Pool
TRE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

\*Used with permission from NERC

Appendix D provides the long-run *marginal capacity addition* generation technology mixes by NERC region in five-year increments. The life cycle GHG emissions (expressed in units of global warming potential) for those regional technology mixes are provided in Exhibit 2-13. The GWP values provided in Exhibit 2-13 were calculated by mapping the technology mixes in Appendix D to the NETL Grid Mix Explorer Tool, which includes LCI data for a variety of generation technologies. [5] The Pls shall use the NERC region that aligns to the study geographical representativeness. If unknown, the U.S. national mix shall be used.

EXHIBIT 2-13. LIFE CYCLE GHG EMISSIONS FOR REGIONAL LONG-RUN MARGINAL CAPACITY ADDITION GENERATION TECHNOLOGY MIXES FOR CAPTURED, GREENFIELD OPTION

REGION	GWP (AR5, 100-YR) KG CO <sub>2</sub> E/MWH DELIVERED						
	2020	2025	2030	2035	2040	2045	2050
U.S. Mix	291	316	333	336	322	320	307
Florida Reliability Coordinating Council	441	147	250	274	209	242	273
Midwest Reliability Organization	136	247	276	289	304	304	278
Northeast Power Coordinating Council	429	361	326	355	369	376	377
Reliability First	388	490	495	495	492	490	486
SERC Reliability Corporation	308	254	315	296	286	268	258
Southwest Power Pool	55	137	141	182	184	197	182
Texas Reliability Entity	318	383	403	413	417	421	358
Western Electricity Coordinating Council	224	275	280	309	298	301	295

Alternative methods for determining the long-run marginal cost are available through some commercial LCA software/database products on the market, various electricity market capacity models, and other public/private modeling resources. The Pls shall use the NETL recommended LCI profile for the Comparison Product System. Additional scenarios for the Comparison Product System using an alternative long-run marginal cost approach may be developed and presented with justification explaining why the alternative method is more appropriate for comparison with the proposed CO2U project.

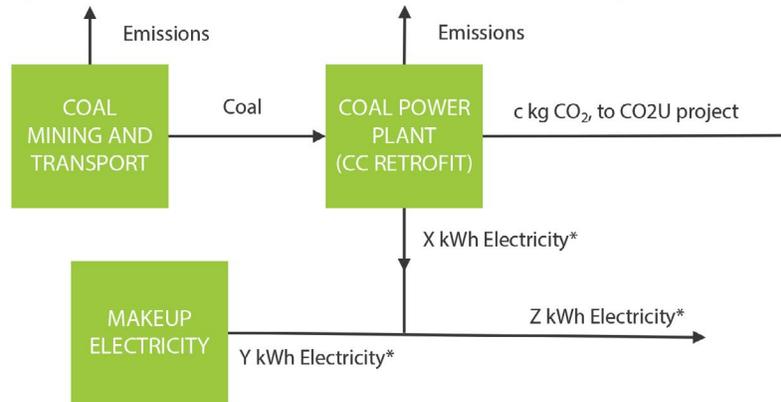
**Comparison Product System Definition for CO<sub>2</sub> Sourced from a Retrofit (Derate) Power Plant Equipped with Carbon Capture Technology**

In this scenario, CO<sub>2</sub> is provided by an existing power plant that is retrofitted with a carbon capture system, where auxiliary energy needs for capture are met by the power plant itself. Facilities retrofitted with capture technology where the auxiliary load is provided by that same facility or unit are de-rated in terms of electrical output. These parasitic loads can complicate analyses. Specifically, compared to a plant without capture, some of the electricity originally dispatched to the grid is instead used to run the capture technology. The plant is unable to make up that electricity to maintain capacity and thus the net generating capacity decreases. In that case, the difference between the former and current rated capacity must be made up by some other source of electricity in the Proposed Product System.

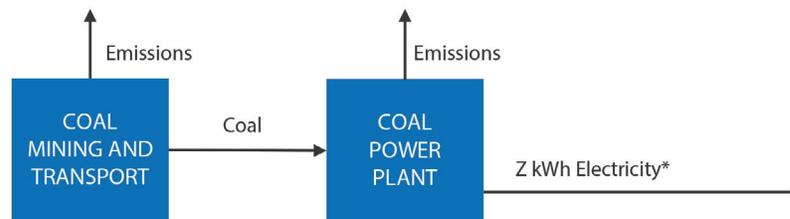
The NETL default parameters CO<sub>2</sub> sourced from a retrofitted (derated) power plant equipped with carbon capture technology shall be a subcritical pulverized coal (SubPC) power plant producing captured CO<sub>2</sub> and electricity co-products. The amount of makeup electricity in the Proposed Product System shall be equal to the derate from adding the carbon capture and compression equipment to the plant (i.e., retrofit), see **Exhibit 2-14**.

#### EXHIBIT 2-14. ELECTRICITY SUB-SYSTEM FOR CAPTURED CO<sub>2</sub> FROM RETROFIT WITH DERATE

### Upstream CO<sub>2</sub> in Proposed Product System



### Electricity Co-product in Comparison Product System



\*The carbon capture plant loses some of its capacity to run the carbon capture equipment, so makeup electricity in the Proposed Product System is required to have the same amount of electricity output. The amount of makeup electricity is defined based on the capacity of the derate (MW) and the assumed operating capacity factor of the plant.

The “makeup” electricity shall be equal to the electricity consumption mix in the generating units geographical representation defined in the study scope (i.e., national, North American Electric Reliability Corporation (NERC) region, NERC sub-region, or balancing authority). Based on the inelasticity of the U.S. electricity market, when an existing power plant is modified in a manner that results in a change (increase or decrease) in the net output of electricity, the “makeup” electricity is equivalent to the electricity consumption mix in the defined study geographical area. Use of the geographical consumption mix for the makeup electricity is technically a proxy data approach. The magnitude of error introduced is deemed minimal and acceptable due to the unknown long-run marginal mix within the specified geographical region. Projects that are nearing commercialization should consider utilizing a regional electricity dispatch model to determine the marginal capacity available within the specified geographical region. The Pls need to verify that the degree of change in the net output can be accommodated/supplied by existing generating assets within the electricity consumption network. The magnitude of the makeup electricity in the Proposed Product System shall correspond to the size of the de-rate.

**Appendix D** provides the makeup generation technology mixes by NERC region in five-year increments. The life cycle GHG emissions (expressed in units of global warming potential) for those regional technology mixes are provided in **Exhibit 2-15**. The GWP values provided in **Exhibit 2-15** were calculated by mapping the technology mixes in **Appendix D** to the NETL Grid Mix Explorer Tool, which includes LCI data for a variety of generation technologies. [5] The Pls shall use the NERC region that aligns to the study geographical representativeness. If unknown, the U.S. national mix shall be used.

**EXHIBIT 2-15. LIFE CYCLE GHG EMISSIONS FOR REGIONAL MAKEUP ELECTRICITY GENERATION TECHNOLOGY MIXES FOR CAPTURED, RETROFIT OPTION**

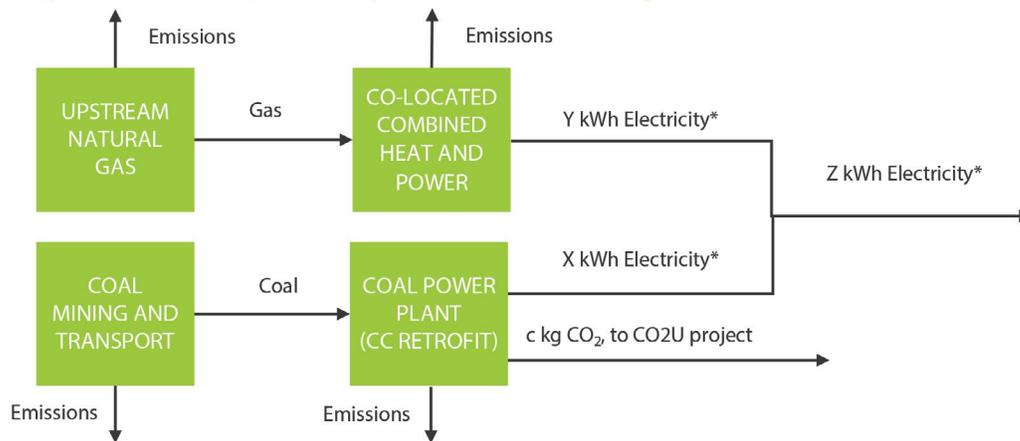
REGION	GWP (AR5, 100-YR) KG CO <sub>2</sub> E/MWH DELIVERED						
	2020	2025	2030	2035	2040	2045	2050
<b>U.S. Mix</b>	499	489	484	472	459	451	439
<b>Florida Reliability Coordinating Council</b>	531	526	526	513	461	459	458
<b>Midwest Reliability Organization</b>	559	588	595	597	596	584	550
<b>Northeast Power Coordinating Council</b>	285	303	280	307	306	310	311
<b>Reliability First</b>	568	559	564	556	554	551	551
<b>SERC Reliability Corporation</b>	530	513	516	488	471	452	437
<b>Southwest Power Pool</b>	541	550	515	490	450	428	405
<b>Texas Reliability Entity</b>	496	490	481	467	473	475	446
<b>Western Electricity Coordinating Council</b>	386	355	338	323	314	313	309

The Comparison Product System shall consider the same power plant as in the Proposed Product System without the carbon capture retrofit. The Proposed Product System includes the same power plant producing less electricity than in the Comparison Product System, where the CO<sub>2</sub> emissions are captured.

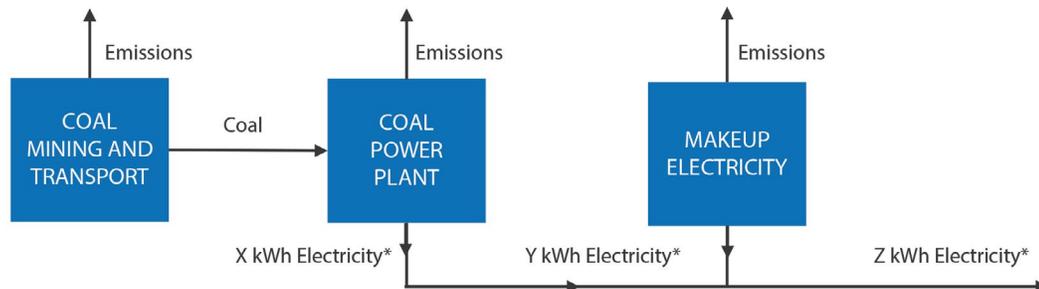
**Comparison Product System Definition for CO<sub>2</sub> Sourced from a Retrofit Power Plant (On-site Co-located Combined Heat and Power) Equipped with Carbon Capture Technology**

In this scenario, CO<sub>2</sub> is provided by an existing power plant that is retrofitted with a carbon capture system. This scenario implicitly assumes that the existing plant electrical output to the grid is not affected in any other way by the retrofit—for example, the net capacity is not de-rated or the heat rate impacted. The auxiliary power to operate the CO<sub>2</sub> capture equipment is assumed to be provided by an on-site co-located combined heat and power plant, as, for example, in the Petra Nova project at the W.A. Parish power plant. [6]

The net output of the retrofitted facility is dependent on the size of the auxiliary unit that provides electricity and steam to the capture unit. If the net output of the facility in the Proposed Product System increases relative to the net output prior to carbon capture, then it is necessary to include additional electricity generation in the Comparison Product System to ensure functional equivalence (see **Exhibit 2-16**). In this scenario, the makeup electricity is added to the Comparison Product System. This is the opposite of the treatment of a retrofit power plant with a derate, where the makeup electricity is added to the Proposed Product System (see **Exhibit 2-14**). As with the retrofit with derate scenario, the Comparison Product System shall model the same power plant as in the Proposed Product System without the carbon capture retrofit.

EXHIBIT 2-16. ELECTRICITY SUB-SYSTEM FOR CAPTURED CO<sub>2</sub> FROM RETROFIT WITH ON-SITE CO-LOCATED COMBINED HEAT AND POWER (NO DERATE)Upstream CO<sub>2</sub> in Proposed Product System

## Electricity Co-product in Comparison Product System



\*The carbon capture plant gains capacity by installing auxiliary power to run the carbon capture equipment, so makeup electricity in the Comparison Product System is required to have the same amount of electricity output. The amount of makeup electricity is defined based on the capacity of the auxiliary combined heat and power unit (MW) and the assumed operating capacity factor of the plant.

The makeup electricity shall be equal to the electricity consumption mix in the generating units geographical representation defined in the study scope (i.e., national, NERC region, NERC sub-region, or balancing authority). Based on the inelasticity of the U.S. electricity market, when an existing power plant is modified in a manner that results in a change (increase or decrease) in the net output of electricity, the makeup electricity supplier is equivalent to the electricity consumption mix in the defined study geographical area.

**Appendix D** provides the makeup generation technology mixes by NERC region in five-year increments. The life cycle GHG emissions (expressed in units of global warming potential) for those regional technology mixes are provided in **Exhibit 2-15**. The GWP values provided in **Exhibit 2-15** were calculated by mapping the technology mixes in **Appendix D** to the NETL Grid Mix Explorer Tool, which includes LCI data for a variety of generation technologies. [5] The Pls shall use the NERC region that aligns to the study geographical representativeness. If unknown, the U.S. national mix shall be used.

The default CO<sub>2</sub> source shall be a SubPC power plant producing captured CO<sub>2</sub> and electricity co-product with a natural gas power plant (modeled as a simple cycle gas turbine [GTSC]) providing the on-site co-located heat and power. The SubPC/GTSC plants function together as one unit, producing the total electricity output from the LCA system boundary, (Z). The NETL default GHG profile for electricity produced from from SubPC power plant with on-site co-located combined heat and power will be provided in the **NETL CO<sub>2</sub>U LCA Documentation Spreadsheet** and the **NETL CO<sub>2</sub>U openLCA LCI database**.

## 2.1.6 DATA REPRESENTATIVENESS

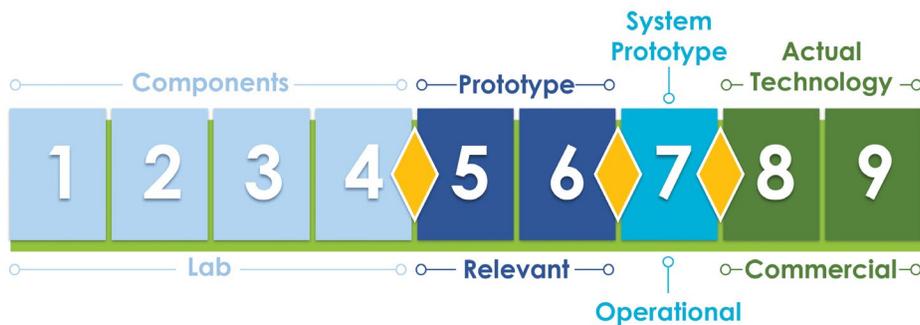
This section describes three specific attributes of data representativeness: technology, geographical, and temporal.

### 2.1.6.1 TECHNOLOGY REPRESENTATIVENESS

The goal and scope of the LCA may vary based on the level of technology development for the proposed PI process. U.S. DOE utilizes the TRL system to benchmark the state of technology development for each project (PI process). **Exhibit 2-17** shows the phases of technology development and the corresponding TRL number. A complete description of the TRL scale is provided in **Appendix B** for reference. The yellow diamonds between TRL 4/5, 6/7, and 7/8 are considered major milestone gates. These gates are used as reference points to establish the minimum expectation for the level of completeness of the LCA. **Exhibit 2-18** describes the LCA expectations based on TRL of the CO2U project.

All technology shall represent current state-of-the-art capabilities available on the commercial market at the time the LCA is conducted. Critical technologies that are “under development” and are expected to undergo significant improvement prior to commercialization shall be identified and any adjustments to the technology profile must be clearly documented with justification. Any changes to the technology representativeness shall be documented in an alternative product system. The “default NETL” Proposed Product System shall represent the current state of development with uncertainty bracketed with low and high bounding scenarios.

**EXHIBIT 2-17. TECHNOLOGY READINESS LEVEL WITH MILESTONE GATES**



**EXHIBIT 2-18. LCA EXPECTATIONS BASED ON TRL OF THE PROJECT**

TRL	LCA EXPECTATION
1-4 <b>Lab-level Research</b>	<p>Screening-level life cycle greenhouse gas analysis. A screening-level analysis is defined as one that allows for approximations and assumptions regarding the process or product of study to provide an initial estimate the life cycle GHG emissions.</p> <p>Early TRL development often provides the greatest opportunity to improve the project design to reduce environmental impacts. Contribution and sensitivity analysis shall be used to assess opportunities for improvement. TRL 1-3 shall demonstrate the potential to have lower GHG emissions than the Comparison Product System with identified research areas/actions to reduce the GHG emissions. TRL 4 LCAs must demonstrate the project has a lower life cycle GHG emission profile than the Comparison Product System. Comparison Product System shall be modeled based on the level of known market information. Industry standard or proxy data are considered acceptable for TRL 1-3. TRL 4 LCAs shall be informed by a technology market assessment or alternative market scenarios demonstrating the break-even life cycle GHG result.</p>
5-6 <b>Scale-up Demonstration</b>	<p>Project-level life cycle greenhouse gas analysis. At this stage in the technology development, knowledge from the scale-up demonstrations shall be used to inform the LCA modeling, site specific conditions shall be used where applicable (known), and the scale of technology market potential shall be considered (consequential effects of market scale).</p>
7 <b>Commercial Scale System Demonstration</b>	<p>Project-level life cycle greenhouse gas analysis. Same as 5-6 Scale-up Demonstration requirements. Expectation is to update the technical performance and site-specific knowledge to validate real-world performance.</p>
8-9 <b>Commercial Scale Learning</b>	<p>Project-level life cycle greenhouse gas analysis. Modeling assumptions shall reflect real-world conditions based on primary data collection from commercial scale system demonstration.</p>

### 2.1.6.2 GEOGRAPHICAL REPRESENTATIVENESS

Geographical boundaries specify the locations of parts or all of a supply chain. This allows calculation of the transport distances between points in the supply chain, the origins of electricity and other energy sources used by unit processes, and specification of other parameters that may change depending on location. It can also serve as the basis for evaluating the extent of interactions among the domestic and global markets of products.

The geographical boundaries of the LCI data are determined by the supply chains required (modeled) to meet the goal and scope of the LCA. It is important to recognize that while the geographical boundary specified in the goal and scope of the LCA and reaffirmed in the long description of the functional unit may vary from the geographic boundary of individual product systems (supply chains). This is acceptable and common. It is important that the inventory data for the modeled product system represent the product that will be delivered to the geographical boundary of the goal and scope of the LCA study. Differences in this representativeness due to data limitations shall be noted in the data quality assessment accompanying the results interpretation section of the study findings.

All CO<sub>2</sub>U projects and their products shall be produced and consumed in the U.S. Supporting supply chains shall represent the geographical origin if known. If unknown, U.S. supply chain profiles shall be considered representative. The level of geographical representativeness shall reflect the level of knowledge about “where” the CO<sub>2</sub>U production facility and CO<sub>2</sub> source are located. If regional or site-specific details are known, then these shall be used in the LCA modeling and clarified in the scope of the LCA.

### 2.1.6.3 TEMPORAL REPRESENTATIVENESS

Timeframes are used to apportion one-time or periodic burdens to the functional unit. The burdens from steady-state operations (e.g., coal extraction at a mine, electricity generation at a power plant, or diesel production at a petroleum refinery) are usually on a basis that directly scales with the functional unit, so these processes are unaffected by temporal boundaries. In contrast, construction burdens and periodic maintenance activities need to be divided by total production during the study period to express it based on the functional unit.

Timeframes can also be used as a basis for improving comparability. This is discussed in **Section 2.1.3** in regard to product comparisons where the compared products have different consumption lifetimes. For example, when considering whether to use asphalt or concrete as the material for a new road, the fact that concrete pavement has a significantly longer lifetime than asphalt must be considered.

In energy systems modeling, analysts often select a 30-year timeframe despite knowing projects often long outlive this timeframe. For example, the average age of coal power plants in the United States is 39 years. [7] Other energy projects may have very different expected lifetimes. The 30-year lifetime for energy projects is widespread in the LCA community and often chosen due to leveled cost of electricity assumptions about loan financing length, [8, 9, 10, 11, 7, 12] and greater uncertainty about the operating requirements beyond 30 years.

NETL’s baseline power LCAs (integrated gasification combined cycle (IGCC), SCPC, and natural gas combined cycle (NGCC)) use a 30-year study period. [15] [16] [17] This timeframe was used because it matches the 30-year book life used by NETL’s financial models of power systems. Therefore, the default temporal boundary for the study shall be 30 years, equivalent to the book life of the power plant providing the CO<sub>2</sub> material input. Emissions from both operative and construction processes within the system boundary are normalized to the study functional unit by levelizing the emissions profile to the stated temporal boundary of interest, typically one year and one unit of product produced. Levelization of the emissions across the temporal boundary represents each year of unit of product produced as having the same environmental profile across the temporal boundary. This is acceptable for the goals of this comparative LCA within this guidance document.

Alternative temporal boundaries may be modeled as alternative product systems with justifications to “why” the change is a better representation of the CO<sub>2</sub> project. The temporal boundaries of the LCA study may differ from the temporal boundary of other supporting analysis sometimes, e.g., techno-economic analyses (TEAs) of the CO<sub>2</sub>U project. The goal is to provide the best representative timeframe for each analysis framework. Consistent lifetimes must be chosen for the Proposed and Comparison Product Systems within the LCA study.

Low-frequency, high-magnitude events (e.g., oil spills, infrastructure failures, and nuclear events) shall be excluded from this LCA. The frequency and impacts of such activities are difficult to characterize and would introduce uncertainty to an LCA without providing significant decision-making capability. LCAs should include the construction, installation, and decommissioning of projects. Construction burdens (e.g., the amount of concrete used for plant construction) and periodic maintenance activities (e.g, catalyst replacement) need to be divided by total production during the study period to express it based on the functional unit.

When considering CO<sub>2</sub>U products, the timescale for how long CO<sub>2</sub> may be stored in a product or system must be considered. For example, CO<sub>2</sub> from flue gas may be used in an algal biomass system and converted to biodiesel. This storage of CO<sub>2</sub> only lasts as

long as the biodiesel remains unoxidized or unused. The CO<sub>2</sub> in this product system is intended for use as a fuel and should not be treated as a permanent sequester of CO<sub>2</sub>. Alternatively, a system that converts CO<sub>2</sub> into a plastic material such as polyethylene furandicarboxylate (PEF) may be considered a long-scale or permanent sequestration of CO<sub>2</sub>. [12] The distinction between the treatment of CO<sub>2</sub> in these two product systems stems from the difference in the timescales for carbon storage; one sees CO<sub>2</sub> returned to the atmosphere in a reasonably short period of time while the other sees CO<sub>2</sub> stored for a sufficiently long period of time, if not permanently. For the purposes of this guidance, CO<sub>2</sub> stored in products greater than 100 years is considered permanently stored. CO<sub>2</sub>-derived products that are expected to release the carbon through use or waste disposal must be considered within the temporal boundary of the product life cycle.

In summary, the NETL default temporal boundary for the LCA study is 30 years of operation (note construction-related activities prior to operation should be leveled across the 30-year study period) and up to 100 years for determining the use and end-of-life boundary for each product. All CO<sub>2</sub>U projects shall estimate the commercial start year within a 5-year increment (e.g., 2020, 2025, 2030, etc.). All construction costs shall be assigned to the start-year of the commercial project and distributed evenly across the study period. The study period for all projects shall be equal to the operation of the CO<sub>2</sub>U primary product of interest service life. End-of-life management, if applicable, shall be considered outside the service life of the primary CO<sub>2</sub>U product of interest, but assigned to the end of year 30 of the study period. End-of-life environmental emissions will be distributed evenly across the study period. Carbon sequestration within a CO<sub>2</sub>U product requires the carbon content of the product to be immobilized (not released to the atmosphere) for a period of time greater than 100 years. The temporal boundary for the life cycle impact assessment method, global warming potential, shall be 100-years.

## 2.1.7 ALLOCATION PROCEDURES

Product systems that include more than one product require decisions regarding allocation of the input and output flows.

ISO 14044 directs LCA analysts to avoid allocation by partitioning the unit processes into subprocesses each of which can be assigned to a co-product. With interconnected and complex systems which have a high degree of integration, partitioning is often not feasible. The next recommended option for avoiding allocation is known as system expansion. With this approach, the product system necessarily includes the functions of all co-products. With system expansion, the relevant co-products in the system are maintained, but one product is assigned as the primary product of interest upon which the system is based (e.g., 1 kg of product A (primary product of interest), *X* km of vehicle travel, and *Y* kWh of electricity). The secondary co-products are scaled to the main co-product in the model. System expansion is the recommended procedure for avoiding allocation. The functions of the expanded system for the Proposed Product System are used to define the functions for the Comparison Product System. LCA results are calculated separately for the Proposed Product System and the Comparison Product System. The results are then compared to one another.

Pls have the option to produce additional analyses for their own purposes that have a single-product functional unit (e.g., 1 kg of product A) by applying either displacement (also called avoided burden or substitution) or allocation. See **Appendix C** for more on applying displacement or allocation.

## 2.1.8 LIFE CYCLE IMPACT ASSESSMENT METHODS FOR RESULTS INTERPRETATION

Below is an overview of the impact categories required and recommended by NETL. The main scope of the LCA is global warming potential (GWP) measured in kilogram (kg) CO<sub>2</sub>e, based on IPCC AR-5, 100-year time horizon, including accounting for climate carbon feedback. The IPCC AR-5, 20-year time horizon results may also be reported but are not required. Other non-greenhouse gas impacts are optional. NETL recommends several impact categories based on the Environmental Protection Agency's (EPA) Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 method for calculating impact assessment results. These are discussed in detail below. Also, NETL recommends the reporting of water consumption. Finally, Pls may propose additional impact categories of interest so long as the source and method are clearly described.

### 2.1.8.1 GLOBAL WARMING POTENTIAL

Global warming is the average increase in the temperature of the Earth's surface and lower atmosphere. Global warming can occur as a result of increased emissions of greenhouse gases (GHGs). [13] Reporting units are kg CO<sub>2</sub> equivalent (CO<sub>2</sub>e). The specification of the time horizon is dependent on which characterization factors are utilized. The global warming potentials (GWP) recommended for use in this study represent climate-carbon feedbacks discussed in Table 8.7 of *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change*. [15] The required GWP is the 100-year time frame, results for the 20-year time frame may also be presented. The GWPs for methane (CH<sub>4</sub>) account for climate carbon feedback and CO<sub>2</sub> from CH<sub>4</sub> oxidation (an appropriate adder for fossil CH<sub>4</sub>). [15] **Exhibit 2-19** provides the required GWPs to be used for the GHGs that were inventoried.

## EXHIBIT 2-19. IPCC GLOBAL WARMING POTENTIALS [14]

GHG	20-YEAR	100-YEAR	UNITS
CO <sub>2</sub>	1	1	kg CO <sub>2</sub> e
CH <sub>4</sub>	87	36	kg CO <sub>2</sub> e
N <sub>2</sub> O	268	298	kg CO <sub>2</sub> e
SF <sub>6</sub>	17,500	23,500	kg CO <sub>2</sub> e

100-year global warming impact factors for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in the *TRACI 2.1 impact assessment method* were added or modified in openLCA and the impact assessment method was renamed “TRACI 2.1 (NETL).” The additions and modifications made are summarized in **Exhibit 2-20**.

## EXHIBIT 2-20. MODIFICATIONS TO TRACI 2.1 TO CREATE TRACI 2.1 (NETL)

SPECIE AND CATEGORY	ADDED OR MODIFIED	VALUE (KG CO <sub>2</sub> E)
Carbon dioxide, biogenic, Emission to air/high population density	Added	1.0
Carbon dioxide, biogenic, Emission to air/low population density	Added	1.0
Carbon dioxide, biogenic, Emission to air/low population density, long-term	Added	1.0
Carbon dioxide, biogenic, Emission to air/lower stratosphere + upper troposphere	Added	1.0
Carbon dioxide, biogenic, Emission to air/unspecified	Added	1.0
Methane, Emission to air/high population density	Modified	36.0
Methane, Emission to air/low population density	Modified	36.0
Methane, Emission to air/low population density, long-term	Modified	36.0
Methane, Emission to air/lower stratosphere + upper troposphere	Modified	36.0
Methane, Emission to air/unspecified	Modified	36.0
Methane, biogenic, Emission to air/high population density	Modified	34.0
Methane, biogenic, Emission to air/low population density	Modified	34.0
Methane, biogenic, Emission to air/low population density, long-term	Modified	34.0
Methane, biogenic, Emission to air/lower stratosphere + upper troposphere	Modified	34.0
Methane, biogenic, Emission to air/unspecified	Modified	34.0
Nitrous Oxide, Emission to air/unspecified	Added	298.0

## 2.1.8.2 ADDITIONAL IMPACT CATEGORIES FOR CONSIDERATION

NETL recommends EPA's TRACI 2.1 method for calculating impact assessment results. [13] TRACI is an impact assessment method developed by the EPA's National Risk Management Research Laboratory. TRACI implements midpoint metrics that describe impacts at some point between the inventory and ultimate damage to the environment. The original version of TRACI was released by EPA in 2002. It was created following a literature survey of existing impact assessment methods, which determined that no tool existed that could provide a comprehensive method applicable to the United States. This analysis utilizes the latest factors available in TRACI 2.1, with modified *characterization factors* for Global Warming Potential to reflect the current state of science from the IPCC. The following describes the recommended non-GWP midpoint impact assessment categories for consideration in evaluating the CO<sub>2</sub>U products.<sup>e</sup>

- **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. [13] Reporting units are kg SO<sub>2</sub>-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”. [15] Reporting units are kg nitrogen (N)-equivalent.

<sup>e</sup> NETL does not use the TRACI 2.1 impact assessment methods that are based on the USETox model due to technical concerns regarding representativeness and completeness of the USETox model.

- **Photochemical Smog Formation Potential (PSFP):** Ground-level ozone, formed by the reaction of NO<sub>x</sub> and volatile organic compounds (VOCs) in the presence of sunlight. [13] 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. [13] Reporting units are kg ozone (O<sub>3</sub>)-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. [16] Smaller diameter particulate matter (2.5 microns or smaller) can be formed by chemical reactions in the atmosphere (e.g., sulfur dioxide and nitrogen oxides). Almost all PM impacts are caused by PM 2.5 microns or smaller (PM<sub>2.5</sub>). [17] Reporting units are kg PM<sub>2.5</sub>-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).

## 2.1.9 DATA REQUIREMENTS, ASSUMPTIONS, AND LIMITATIONS

This section of scope definition refers to assessments of completeness as well as documentations of any assumptions and limitations of the modeled data.

### 2.1.9.1 COMPLETENESS REQUIREMENTS

An engineering-based carbon and energy balance shall be conducted across the life cycle system boundary to determine the level of completeness. The LCA shall include at least 99% of the carbon and energy inputs and outputs to the system boundary. Completeness shall be demonstrated based on a carbon and energy balance. Completeness shall be tested by determining if inclusion of secondary or tertiary processes to the system boundary would change the result at the third decimal place (significant digit).

Defining the system boundary may also include determining what processes can be excluded from the study. Screening is often necessary to determine if a process must be included in study boundaries.

ISO sets forth guidance in ISO 14044, “Environmental management — Life cycle assessment — Requirements and guidelines.” [2] The guidance establishes *cut-off criteria* based on three criteria: mass, energy, and environmental significance. The document states that “an appropriate decision, when using mass as a criterion, would require the inclusion in the study of all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modelled.” [2] Similar language is used for energy as a criterion. The guidance also states that “decisions on cut-off criteria should be made to include inputs that contribute more than an additional defined amount of the estimated quantity of individual data of the product system that are specially selected because of environmental relevance.” [2]

Making cut-off decisions based on one of these criteria may omit important results from the study. As such, all three criteria shall be considered when drawing initial cut-off criteria for inclusion of inputs and outputs.

It is important for clarity that the cut-off criteria for initial inclusion of inputs and output is clearly described. Other assumptions important to these decisions must also be clearly documented in such a way that results may be replicated. ISO 14044 states, “The system should be described in sufficient detail and clarity to allow another practitioner to duplicate the inventory analysis.” [2] This requirement is consistent for this guidance document.

CO<sub>2</sub>U does not require special treatment in LCA regarding cut-offs. It is important, as with all LCA analysis, that systems for CO<sub>2</sub>U projects also follow the standards put forth in ISO 14044. It would be easy to let an input such as a catalyst fall outside the cut-off criteria on, for example, a mass basis given the relative amount of CO<sub>2</sub> used. However, catalysts may have relatively higher energy requirements and could have larger environmental significance that should not be ignored.

### 2.1.9.2 SENSITIVITY AND UNCERTAINTY ANALYSIS

Pls shall complete a sensitivity analysis in which each parameter in the model is varied 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). NETL minimum expectations are 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 and Comparison Product System modeled. Pls shall describe under what modeling conditions the results of the LCA

study would change the outcome of the comparison; a break-even analysis is one technique often used to determine the technical boundaries for environmental preferability.

### 2.1.9.3 REPORTING UNITS AND METHODS OF COMPARISON

To ensure consistency with NETL standards, Pls shall report in the International System of Units (SI). All results shall be reported in scientific notation (e.g., 2.34+01 kg CO<sub>2</sub>e).

NETL default comparison requirement is three forms/metrics:

1. stacked bar chart with uncertainty bars
2. ratio of Proposed/Comparison Product System
3. percent change calculation of the Proposed Product System from the Comparison Product System

Pls shall calculate the ratio and percent change between the Proposed Product System(s) and the Comparison Product System(s) for each *impact category* and display the results in a table. The ratio shall be calculated as follows for each impact category:

$$\text{Ratio} = \frac{\text{Total Proposed Product System}}{\text{Total Comparison Product System}} \quad \text{EQUATION 2-1}$$

“Total” refers to the result for a given impact category. The percent change shall be calculated as follows for each impact category:

$$\text{Percent Change} = \frac{\text{Total Proposed Product System} - \text{Total Comparison Product System}}{\text{Total Comparison Product System}} \times 100 \quad \text{EQUATION 2-2}$$

### 2.1.9.4 STUDY LIMITATIONS – DATA QUALITY ASSESSMENT

According to ISO 14044, “data quality requirements shall be specified to enable the goal and scope of the LCA to be met.” [2] Specifically, a data quality assessment shall consider the following elements:

1. Technology representativeness (see **Section 2.1.6.1**)
2. Geographical representativeness (see **Section 2.1.6.2**)
3. Temporal representativeness (see **Section 2.1.6.3**)
4. Data completeness (see **Section 2.1.9.1**)
5. Precision and uncertainty (see **Section 2.1.9.2**)
6. Consistency – assessment of uniformity of methods across the study
7. Reproducibility – assessment of ability for a third party to produce the same results

The treatment of missing data shall be included in this assessment. Acceptable approaches for missing data should result in a value that can be documented and explained.

## 2.2 INVENTORY ANALYSIS

“Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study.” [1] [2]

### 2.2.1 MODELING PLATFORM

Modeling is the translation of real-world activities (or *proposed* real-world activities) into mathematical relationships. Modeling refers to the compilation of unit processes into a network of unit processes that is consistent with the boundaries that have been defined for an LCA. Modeling and calculations can be done manually (e.g., using spreadsheet software like Microsoft Excel™) or by using LCA software packages. As noted in **Section 1.5**, Pls are strongly encouraged to use openLCA to conduct the analysis required by this document.

LCA software is best for the management of unit processes and ease of results calculation and sensitivity/uncertainty analysis.

LCA software contains predefined templates and meta data fields for consistency and ease of unit process documentation. Pls may choose to develop and document the unit process within the software tools or use other model and documentation formats. The expectation is that all models and unit processes be clearly documented to understand the data sources used, the mathematical relationships derived, and the representativeness of the model. All models and documentation shall accompany the LCA report/ results (see **Section 6.0**).

### 2.2.1.1 OPTION 1: OPENLCA

openLCA is an open source software available free to download at [openLCA.org](https://openlca.org). openLCA includes Monte Carlo simulation, in-software results charts, and contribution trees. GreenDelta maintains and updates the openLCA software and makes new versions available for download at [openLCA.org](https://openlca.org). The openLCA Nexus makes third-party databases available in a format that is compatible with openLCA. The third-party datasets include LCI data and impact assessment methods.

### 2.2.1.2 OPTION 2: PI SPREADSHEET MODEL

If Pls choose Option 2, then Pls shall complete the **NETL CO<sub>2</sub>U LCA Documentation Spreadsheet**, so that NETL can review their spreadsheet model. The **NETL CO<sub>2</sub>U LCA Documentation Spreadsheet** requires Pls to include diagrams of their LCA model, with each unit process labeled with a unique number, unit process data for each labeled unit process, and calculations (when applicable). Pls may also include software screenshots.

### 2.2.1.3 OPTION 3: ANOTHER LCA SOFTWARE PLATFORM OR TOOL

Option 3 allows for the use of another LCA software or analysis tool instead of openLCA. Pls are free to use any LCA software or analysis tools available to them. Other software and tools can include any LCA software or tool for conducting LCA. Two common LCA software packages that are available for pay include SimaPro by PRe and GaBi by thinkstep. In addition to providing LCA software, GaBi also creates its own LCI data. There are also other free, open source LCA software packages, in addition to openLCA, such as Umberto. It should also be noted that LCA can be conducted by hand, in a spreadsheet software, or other software, but is more burdensome to do so. Pls shall use Option 2 in conjunction with Option 3 when an LCA software/database is used but not provided for public release as part of the project's Final Scientific/Technical Report.

Disclaimer: NETL does not endorse or recommend any specific third-party LCA software. It is the responsibility of the Pls to evaluate and select any third-party resources for accuracy and representativeness to the study of interest.

## 2.2.2 DATA COLLECTION

When conducting an LCA, it is necessary to research all significant production, transport, waste processing, and construction processes. In lieu of primary (field-level) data collection, the use of publicly available information is the common research method. Environmental impact statements, data developed by government agencies, manufacturer specifications, data compiled by trade organizations, journal articles, and conference proceedings are examples of public sources of information that can be used to develop life cycle inventory data.

The objective of researching a life cycle is to identify all processes that directly or indirectly contribute to the production of the product of interest. It is easy to get distracted, either gathering too much information on a process or overlooking a key process altogether. Identifying the unit processes that should be included in a life cycle is both an art and science, but by conducting a literature review, looking at LCAs of similar systems, and talking to subject matter experts, one can arrive at a level of detail that accounts for key processes without spending too much time researching insignificant processes (see **Section 2.1.9.1**).

NETL has developed an extensive library of unit processes to model power generation and the associated supply chains. A relevant subset of that data is made available to Pls in the **NETL CO<sub>2</sub>U openLCA LCI Database** including data on fuel production, fuel combustion, materials, transportation, electricity generation, and fossil power CO<sub>2</sub> sources (see full list in **Appendix E**). The Pls will be responsible for developing any missing data, with emphasis on the boundaries of their process. The following sections describe the approaches for doing so.

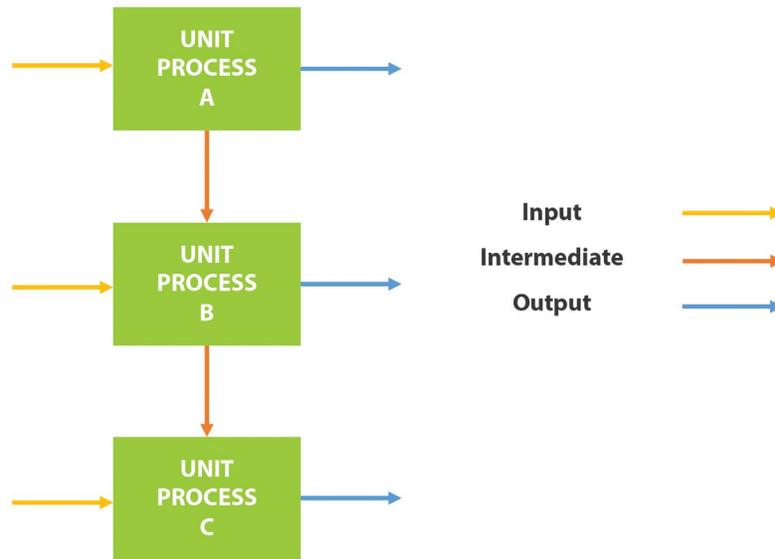
### 2.2.2.1 UNIT PROCESS STRUCTURE

Unit processes are the building blocks of an LCA and summarize the inputs and outputs of a process. One way to learn about unit processes is to look through NETL's unit process documentation (available in NETL's unit process library). [18] NETL's data summary (DS) sheets are Microsoft Excel™ files with detailed calculations, and NETL's documentation file (DF) sheets are Microsoft Word™ documents that discuss the data development approach for the unit processes. [18]

The four components of NETL's unit processes are parameters, inputs, outputs (or *intermediate flows* if connected to another unit

process), and the *reference flow*. An example is depicted in **Exhibit 2-21**. The terms intermediate flows and technosphere flows are synonymous. When referred to in the context of a unit process, the reference flow is the primary product. However, when considered in the context of a product system, the reference flow of the unit process becomes an intermediate flow.

**EXHIBIT 2-21. UNIT PROCESS CONNECTIVITY AND FLOW NAMING CONVENTIONS (ADAPTED FROM ISO 14044 [1] [2])**



The use of parameters makes unit processes flexible and assists with sensitivity and uncertainty analysis. For example, an efficiency parameter in a unit process for a coal-fired power plant can be used to change the amount of coal fuel that is combusted per unit of electricity produced. The mass composition of methane in raw natural gas can be used as a parameter that affects the share of methane in process vents at natural gas extraction sites and the combustion emissions from flares at natural gas extraction sites. NETL's bottom-up unit processes rely heavily on parameterization, because they use scientific principles or engineering concepts to calculate inputs and outputs. Not all unit processes have parameters. For example, some processes utilize static process simulation results. Such unit processes are black boxes; they can be used to model specific scenarios but cannot be adjusted in response to broader system variables.

**Inputs** are fuels or raw materials used by a unit process (e.g., the mass of coal used per MWh power generated). Input values can be static or controlled by parameters. Black box unit processes use single values for inputs, while bottom-up unit processes use parameters that change input values based on process variables. When incorporated in a life cycle model, "tracked" inputs are linked to upstream unit processes. Not all inputs are tracked. If an input is a natural resource that has not undergone any industrial activity, it is not necessary to link it to an upstream unit process. The surface water or groundwater withdrawn by a power plant, ore extracted at a mine, raw natural gas extracted at a wellhead, or air consumed by an air separation unit are examples of inputs that are inventoried by unit processes, but do not need to be linked to upstream unit processes. In LCA terminology, these are referred to as *elementary flows*.

**Outputs** are products, emissions, or wastes from a unit process. For example, the outputs from NETL's SCPC operational unit process are electricity (the only product inventoried by the unit process), air emissions, water effluents, and discharged water. Tracked outputs are used by downstream unit process and can also be referred to as intermediate flows. For example, the electricity produced by an SCPC power plant is a tracked output that is linked to the downstream input to the unit process for electricity transmission and distribution. It is possible for a unit process to have two or more tracked outputs, requiring allocation approaches to put on the basis of a single output (as explained in **Appendix C**). Outputs to nature should be modeled and reported but are not considered a "tracked" flow in LCA terminology. In LCA terminology, these are referred to as "releases." For example, air emissions, water effluents, or discharged water that does not undergo further treatment are inventoried by unit processes but are not connected to downstream unit processes.

The reference flow is the denominator of a unit process and is used to connect the unit process to other unit processes. All other inputs and outputs in a unit process are scaled to the basis of the reference flow. For example, the reference flow for NETL's SCPC coal power plant operational unit process is one MWh of produced electricity, so all coal inputs and air emissions are scaled to the basis of one MWh of production. The reference flow does not necessarily have to be the primary product of a unit process. When used in the context of an entire product system, the reference flow can be thought of as equivalent to the functional unit of the primary product of interest. Specifically, the reference flow "fulfills the function expressed by the functional unit." [1] [2]

**Consumables** are inputs that are fundamentally changed in a process or become part of the final product or an emission. Examples of consumables include electricity and material feedstocks. Water is a consumable when it becomes part of the final product or becomes a wastewater output. Consumables shall be included in mass balance or carbon balance checks.

**Non-consumables** are inputs that facilitate a process, but do not become a part of the product. These include things like infrastructure, machinery, catalysts, or working fluids. Non-consumables are included in a unit process when their impacts must be accounted for upstream and/or downstream (see **Section 2.1.9.1**). Some non-consumables are degraded in the process and must be replaced or supplemented. Replacement of non-consumables needs to be accounted for in an LCA. Non-consumables that do not change would simply have the same input and output amounts. The degradation of non-consumables can be accounted for by including a waste output emission. When a non-consumable lasts beyond the period of the unit process, the impact of that non-consumable can be scaled to be a portion of its lifetime. For example, there may be a unit process that summarizes the total impact of a piece of infrastructure over its lifetime. If one connects the infrastructure unit process to a product manufacturing unit process that uses that infrastructure as an input for only one year, a scaling factor of  $1/x$  can be applied to that flow to scale down the impact to one year, where  $x$  equals the lifetime of the non-consumable in years.

### 2.2.2.2 ENVIRONMENTAL INVENTORY DATA

Emissions and other output data in unit processes are ultimately linked to an impact assessment method (see **Section 2.1.8**) to calculate environmental impacts, so it is imperative to report all relevant outputs in each unit process. For the purposes of this guidance, Pls shall at least report the following GHG emissions in their unit processes: CO<sub>2</sub>, methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) where applicable. Pls are encouraged to include all available emissions species, especially those noted in **Exhibit 2-22**.

#### EXHIBIT 2-22. EXAMPLE OF IMPORTANT OUTPUTS TO REPORT BASED ON NETL LCI METRICS

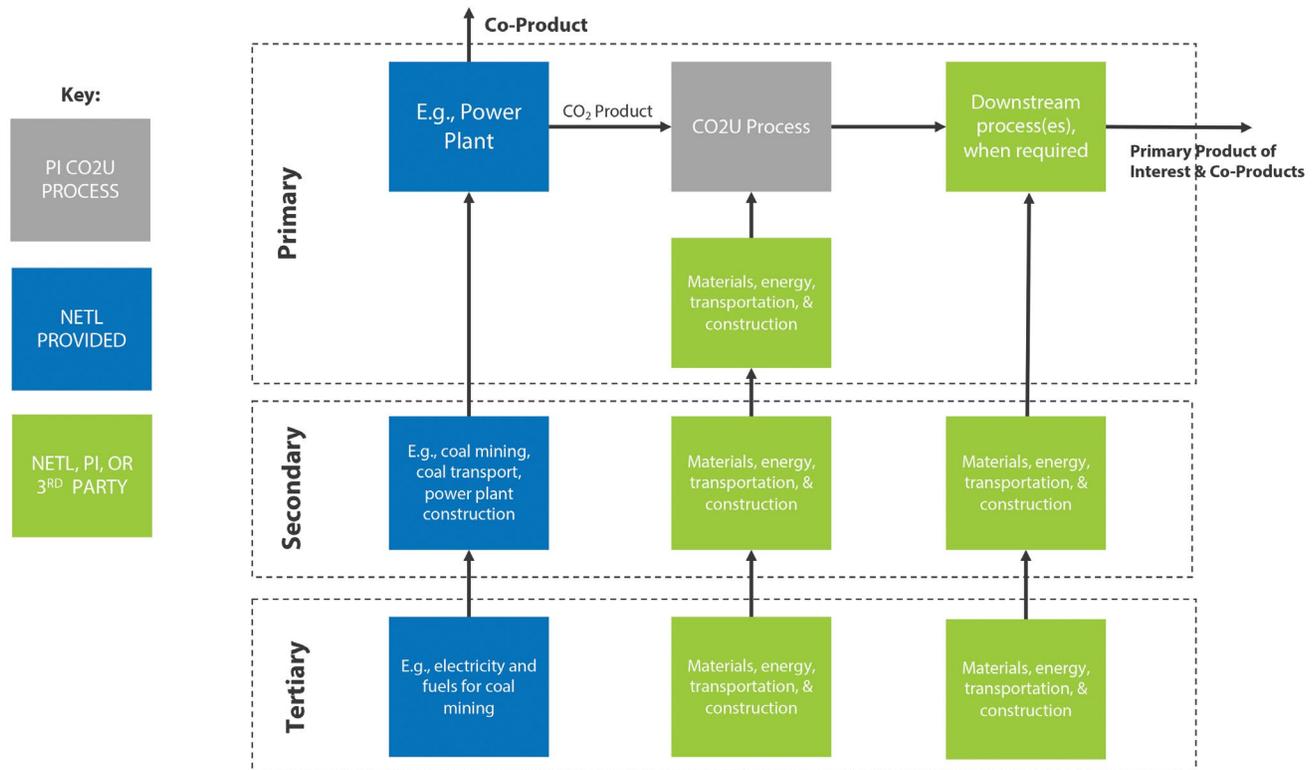
CATEGORY	SPECIES	REPORTING METRIC PER FUNCTIONAL UNIT & UNIT PROCESS REFERENCE FLOW
<b>GHG Emissions</b>	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, Sulfur Hexafluoride (SF <sub>6</sub> )	Mass Emitted to Atmosphere
<b>Criteria Air Pollutants</b>	Nitrogen oxides (NO <sub>x</sub> ), Sulfur Dioxide (SO <sub>2</sub> ), Carbon Monoxide, Ozone, Particulate Matter (≤ PM10), Lead (Pb)	Mass Emitted to Atmosphere
<b>Species of Interest</b>	Mercury, Ammonia, Hydrogen Chloride, Hydrogen Fluoride, Nitrogen Monoxide, Radiation, Non-Methane Volatile Organic Compounds (≥1%), Other Heavy Metal (≥1%)	Mass Emitted to Atmosphere
<b>Solid Waste</b>	Heavy Metals to Soil (≥1%), Solid Waste (unspecified)	Mass Emitted
<b>Raw Materials</b>	Coal, Crude Oil, Natural Gas, Uranium, Unconventional Fossil Resources, Renewable Resources	Mass Extracted Energy Content of Material
<b>Water Emissions</b>	Aluminum, Ammonium/ammonia, Heavy Metals (≥1%), Hydrogen Chloride, Nitrate, Nitrogen, Phosphate, Phosphorous	Mass Emitted to Body of Water, Volume of Water Consumed
<b>Water Use</b>	Volume Withdrawn from Surface or Groundwater Sources, Volume Returned to Receiving Body of Water	Volume of Water Withdrawn, Volume of Water Consumed
<b>Direct Land Use Area</b>	Area of Land Type Changed, Land Type Prior to Use (crop, grassland, or forest)	Area of Land Changed
<b>Indirect Land Use Area</b>	Area of Agricultural Land Development	Area of Land Changed

### 2.2.2.3 UNIT PROCESS DATA DEVELOPMENT APPROACHES

The development of data for life cycle models is a time-consuming process that requires a background in science and engineering, the willingness to gather information from disparate sources and normalize it to a common basis, and the ability to translate real-world phenomena into mathematical relationships.

Development and selection of unit process data is a balance between data quality, utility, and time and resources to create custom models. In the field of LCA, there is no distinction between “good” and “bad” data, only “fit for purpose” based on the goal and scope of the study. For this guidance document, the expectation is that the Pls will develop a custom, parameterized unit process or unit processes of all operations within the operational control of the CO2U project. **Exhibit 2-23** illustrates this point and defined nomenclature related to primary, secondary, and tertiary unit processes within a typical LCA study. Four general methods for data development are described in the following sections.

EXHIBIT 2-23. UNIT PROCESS DEVELOPMENT MINIMUM EXPECTATIONS AND NOMENCLATURE



**Process Based (Bottom Up)**

The bottom-up approach uses engineering and other relationships to calculate the energy or material flows of an activity. For example, a bottom-up calculation of the CO<sub>2</sub> emissions from pipeline compressors would factor variables for the thermodynamic properties of fluid compression, compressor efficiency, spacing between compressors, pipeline pressure drop, split between natural gas and electricity use by pipeline compressors, combustion chemistry for natural gas, and flow rate of natural gas through the pipeline.

In the NETL CO<sub>2</sub> compression unit process, the power required to pump the CO<sub>2</sub> is calculated using the **Equation 2-3** found in literature [21]. [22]

$$Power = \frac{1000 * 10}{24 * 3600} * \frac{CO_2 \text{ flow rate} * (Pressure_{final} - Pressure_{cut-off})}{CO_2 \text{ density} * pump \text{ efficiency}} \quad \text{EQUATION 2-3}$$

The energy used for compression uses a set of equations with similar parameters from the same reference. Water use and CO<sub>2</sub> emissions were calculated using emissions factors and data from existing cooling towers. By tying these calculations to a common basis – 1 kg CO<sub>2</sub> ready for pipeline transport – a complete unit process as developed. Additionally, the various components and assumptions as part of the bottom up calculation can be parameterized for the purposes of sensitivity and uncertainty analysis.

**System Based (Top Down)**

The top-down approach uses data from outside the boundaries of a process to calculate energy and material flows. In contrast to the bottom-up calculation of pipeline emissions described above, a top-down calculation of CO<sub>2</sub> emissions from pipeline compressors could use national pipeline CO<sub>2</sub> inventories calculated by the EPA or corporate CO<sub>2</sub> emissions reported by pipeline operators, divided by the corresponding natural gas throughput, to arrive at a similar emission profile.

The top-down method is accurate (presuming that the source data are accurate). However, top-down unit processes are not as flexible as bottom-up unit processes as they lack parameters. If the goal of an LCA is to calculate total burdens for a product, then top-down unit processes are sufficient. But if the goal of an LCA is to drill down to the sub-process level and use parameters to test system dynamics, then top-down data will not be sufficient.

## Black Box

A black box unit process is developed from a set of data that completely describes the inputs and outputs of a process. The unit processes for NETL's SCPC, IGCC, and NGCC power plants are examples of black box unit processes. These unit processes are based on the results of thermodynamic models developed by techno-economic experts and published in detailed reports. [22]

The black box approach is the easiest approach for developing a unit process. The summary tables in the bituminous baseline provide essential data on fuel consumption rates, CO<sub>2</sub> emissions, NO<sub>x</sub> emissions, and SO<sub>2</sub> emissions per unit of electricity generated.

One limitation of the black box approach is that complete data sets that align exactly with the boundaries of a unit process are rarely available. Another limitation of black box unit processes is that they have limited applicability. They are based on specific technologies and do not have parameters that allow them to be adapted to other technologies.

## Economic Input-Output Data

Data gaps can also be filled by using an economic input-output (EIO) model.<sup>f</sup> The EIO method for boundary definition uses EIO data derived from the U.S. inter-industry economic transaction matrices and publicly available environmental data to arrive at comprehensive, industry-wide environmental impacts. [23] For the United States, the implementation of EIO modeling is found in the Economic Input-Output Life Cycle Assessment (EIOLCA) model. If the amount and relative cost of a material is known, feedstock, or fuel needed for a flow, the EIOLCA model calculates the LCI data for that flow based on its impact through the U.S. economy. The advantage of this method, besides being publicly available and relatively easy to use, is that when the EIO method is used to collect data for a secondary or tertiary flow, all subsequent high-order flows are also captured in that data giving a conservative estimate of impacts; because of this, the EIO model provides the most efficient method to capture data as close to the elementary flows for a system as possible. The disadvantages are the large range of uncertainty associated with data values due to old data and vague flow descriptions, which are often not specific enough from an LCA standpoint; because of this, EIO models are not recommended for first or even large second-order process flows. However, especially for comparative assessments, EIO models can provide extensive data with little effort. This guideline does not discuss the procedure to use the EIOLCA model; the reader is referred to the reference sources and links above for more information.

### 2.2.2.4 EXISTING UNIT PROCESS DATASETS

The above examples are an overview of common data development approaches. A unit process does not need to use a single method exclusively; unit processes are often a mix of data development methods. A comprehensive perspective of data development is provided by the unit process documentation in NETL's unit process library. [18]

Third-party data involves using LCI profiles from secondary sources. LCI databases exist (either free of charge or available for purchase) that provide data for many secondary and tertiary process flows. The advantage to using third-party data is that there is additional study depth that is achieved when including secondary flows without the level of effort associated with developing all additional life cycle data sets. The disadvantage is the lack of transparency associated with the available databases; these data are often based on proprietary information that is aggregated to protect the original data source. For most LCAs, the use of third-party data is sufficient for secondary or higher-level unit processes as shown in **Exhibit 2-23**.

Existing LCI unit process resources can be used to reduce the time and cost associated with developing unit process data. Existing unit process data can be used as is or modified to better represent the process of interest. The following are examples of existing unit process data resources.

1. **NETL CO2U openLCA LCI Database** (see full list in **Appendix E**)
2. NETL Unit Process Library [18]
3. U.S. Federal Commons LCA Database (<https://www.lcacommons.gov>)
4. openLCA Nexus (<https://nexus.openlca.org/>)
5. Other commercial LCA software databases
  - thinkstep GaBi
  - ecolnvent
  - SimaPro

Disclaimer: NETL does not endorse or recommend any specific third-party LCI database. It is the responsibility of the PIs to evaluate and select any third-party resources for accuracy and representativeness to the study of interest.

<sup>f</sup> Found at [www.eiolca.net](http://www.eiolca.net).

### 2.2.2.5 PROXY DATA

Proxy data can be used to represent missing data if a material or energy input is important to the study conclusions. Proxy data is data that is assumed by the Pls to be a similar representation of a process for which data does not exist. For example, using an existing profile of a conventional catalyst material input to represent an advanced catalyst material composition. Therefore, if unit process data gaps existing in the LCA model, then document the data gap and test the effect of the final results using sensitivity analysis. For example, if a unit process for a material does not exist, identify at least two proxy data sets equivalent to the mass of the required material input that would theoretically bound a low and high environmental profile for a similar type of material. Double the mass of the requirement for each profile and test the sensitivity of the study results to the importance and relative changes in study-level results. If the study results are determined to be sensitive (materially changes the interpretation of the study findings) then this deficiency and its impact on results shall be prominently noted with the study conclusion; see **Section 2.2.3.2** on sensitivity analysis. Alternatively, if time and resources permit, conduct primary research and modeling to fill the data gap.

## 2.2.3 DATA CALCULATION AND QUALITY ASSESSMENT

There are two steps for modeling in LCA: 1) connecting the unit processes and scaling them to the functional unit and 2) applying the impact assessment factors of an impact assessment method to turn inventory quantities like kg of methane per functional unit into an environmental impact like GWP (expressed as kg CO<sub>2</sub> equivalent per functional unit). This section describes the procedures related to life cycle inventory modeling; see **Section 2.3** for details on life cycle impact assessment modeling. Life cycle inventory modeling requires the assembly of unit processes to represent the product system of interest. Once assembled, the completeness of the model and the unit process relationships need to be verified to ensure the representativeness meets the goal and scope of the study.

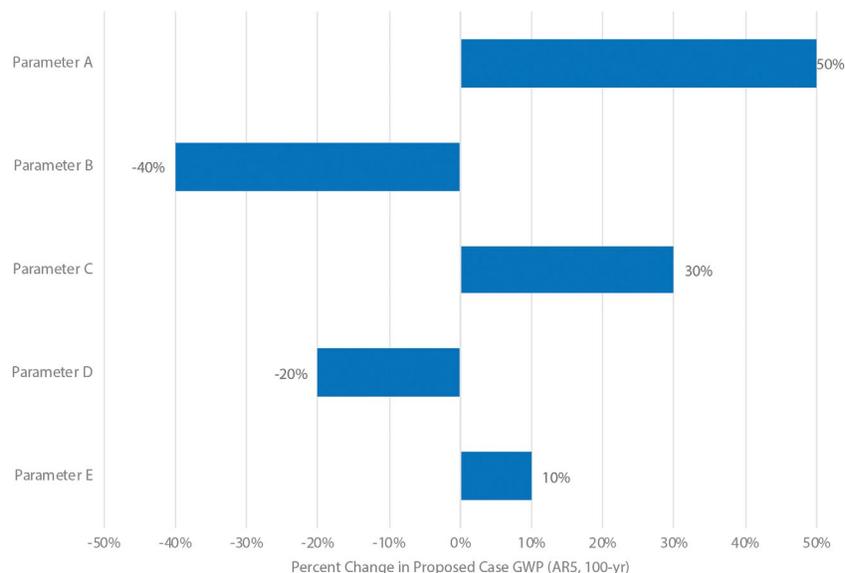
### 2.2.3.1 COMPLETENESS CHECK

An engineering-based carbon and energy balance shall be conducted across the life cycle system boundary to determine the level of completeness. The LCA shall include at least 99% of the carbon and energy inputs and outputs to the system boundary. Completeness shall be demonstrated based on a carbon and energy balance.

### 2.2.3.2 MODEL SENSITIVITY CHECK

The purpose for testing the model sensitivity is to confirm that the model responds as would be expected. One common approach to understanding the impact of changing key parameter values is to perform a one-at-a-time sensitivity analysis. In this approach, the variables are altered individually by the same percentage (often a 100-percent increase) maintain all other parameters as the expected values and the corresponding life cycle result is recalculated. An example of this approach is provided in **Exhibit 2-24**. Five of the key parameters in the example are tested and the resulting impact on the GWP for the Proposed Product System are documented. The results of the sensitivity analysis can be used to focus data collection and refinement efforts as well as provide a clear understanding of the importance of the key model parameters. Based on the algorithm, one-at-a-time sensitivity analysis cannot account for any correlation between parameter values.

**EXHIBIT 2-24. ONE-AT-A-TIME SENSITIVITY ANALYSIS EXAMPLE FIGURE**



### 2.2.3.3 ALLOCATION PROCEDURES

Allocation is a technique of assigning environmental burdens to two or more co-products to describe the environmental effects of a single product in the absence of the other co-products. Allocation can occur at both the product system and unit process modeling levels in LCA. Each is described below.

#### Product System

As noted in **Section 2.1.7** the Pls shall avoid allocation at the product system level by utilizing system expansion with a multiproduct functional unit. In addition to the required result using system expansion, Pls may also utilize alternative methods described in **Appendix B** to calculate the results on the basis of a single product of interest.

#### Unit Processes and Secondary Supply Systems

As noted in **Section 2.1.7**, the Pls shall avoid allocation at the product system level by utilizing system expansion with a multiproduct functional unit. However, there will necessarily be processes/products within the secondary supply systems that do require allocation (e.g., production of diesel fuel from a petroleum refinery). For any instances of allocation, the Pls shall denote the allocation approach that was utilized. For third-party data, it is recommended that the Pls review the allocation approach to ensure concurrence.

## 2.3 IMPACT ASSESSMENT

According to ISO 14044 Life Cycle Impact Assessment (LCIA) involves the following [2]:

1. Selection of impact categories
2. Assignment of LCI to impact categories (classification)
3. Calculation of category indicator results (characterization)

The U.S. DOE Carbon Utilization Program minimum requirement is a life cycle greenhouse gas analysis using the IPCC, AR5, 100-year time horizon characterization factors (see **Exhibit 2-19**). Pls have the options 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 in the openLCA LCI Database. These values are based on EPA's TRACI 2.1 method for calculating impact assessment results. [13] Note, the values provided in the TRACI 2.1 method are based on midpoint impacts as opposed to endpoint impacts, minimizing the assumptions necessary. Endpoint impacts connect the emissions to damage, which results in a higher level of uncertainty. As an example, the midpoint for global warming potential would be an increase in the atmospheric concentration of GHGs, while the endpoint impact would be sea level rise.

- required: global warming potential (kg CO<sub>2</sub>e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100
- optional: global warming potential (kg CO<sub>2</sub>e), based on IPCC AR5, 20-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-20
- optional: non-greenhouse gas impact assessment methods; NETL recommends the following U.S. EPA TRACI mid-point impact assessment methods for consideration
  - acidification potential (kg SO<sub>2</sub>e); abbreviation: AP
  - particulate matter formation potential (kg PM<sub>2.5</sub>e); abbreviation: PMFP
  - photochemical smog formation potential (kg O<sub>3</sub>e); abbreviation: PSFP
  - eutrophication potential (kg Ne); abbreviation: EP
  - ozone depletion potential (kg CFC-11e); abbreviation: ODP
- optional: water consumption (l); abbreviation: WC

Individual species in the LCI can be assigned to one or more impact categories depending on the selected impact framework. The mapping of LCI to impact categories is prescribed in the TRACI 2.1 method. This step is referred to as the classification of the LCI.

Following classification, LCIA results are calculated using a set of characterization factors specified by the selected method, in this case TRACI 2.1. Each impact category includes a set of characterization factors for each of the species that contribute to that impact. The product of the LCI and the characterization factors for each impact category yield results that are in a set of common units for that impact category (e.g., CO<sub>2</sub>e for global warming potential).

Note, NETL does not recommend normalization and weighting life cycle impact assessment results for the U.S. DOE Carbon Utilization Program LCA studies due to the subjective and value-based approaches required for those methods.

### 2.3.1 DATA QUALITY ASSESSMENT

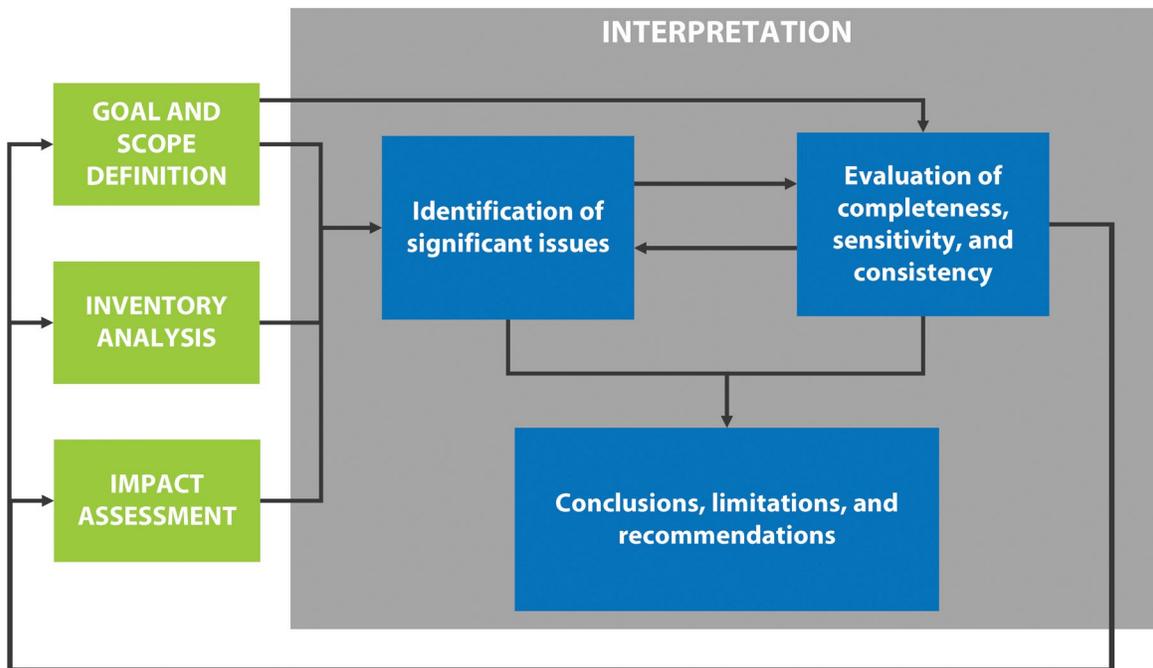
A critical component of the LCIA is the evaluation of the approach and results. Pls shall describe any known data limitations, omissions of inventory data, that may affect the interpretation of each impact categories result. A completeness check should be performed to determine if sufficient data exists to report on each impact category. The completeness is assessed based on environmental relevance for each impact category; 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. The results of the environmental relevance shall be documented as part of the modeling effort and the LCA study report shall contain a statement describing 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.

## 2.4 INTERPRETATION

“Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together or, in the case of LCI studies, the findings of the inventory analysis only. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations. The interpretation should reflect the fact that the LCIA results are based on a relative approach, that they indicate potential environmental effects, and that they do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks. The findings of this interpretation may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study. Life cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA, in accordance with the goal and scope definition of the study. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal.” [2]

As shown in **Exhibit 1-1**, the four phases of LCA are iterative. The primary three phases (goal and scope definition, inventory analysis, and impact assessment) each include interpretation requirements. The purpose of interpretation after each phase is to refine and improve the study. This expanded approach is depicted in **Exhibit 2-25**.

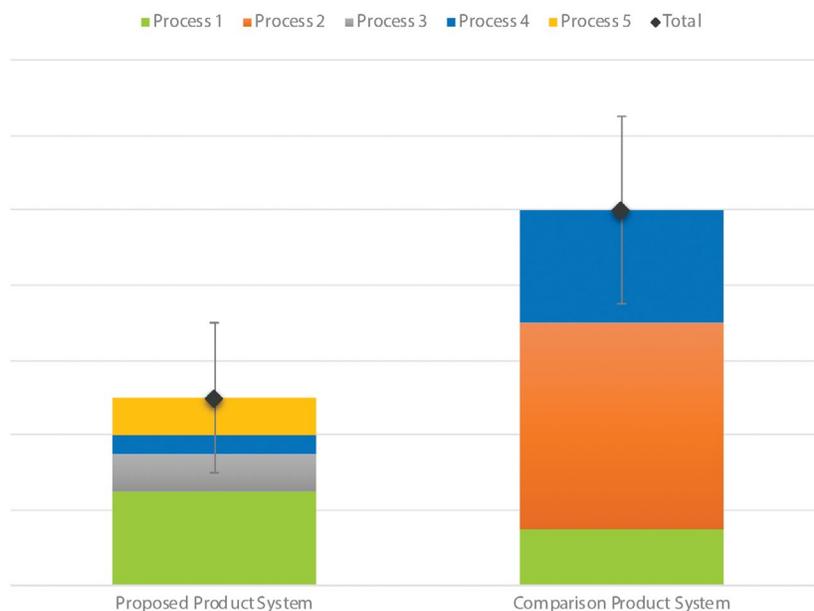
**EXHIBIT 2-25. EXPANDED VIEW OF INTERPRETATION LCA PHASE (ADAPTED FROM ISO 14044 [1, 2])**



### 2.4.1 PRODUCT SYSTEM COMPARISON METHODS

Pls shall generate a contribution analysis and display results as a stacked bar chart or charts that includes the Proposed Product System, the Comparison Product System and two sensitivity scenarios per product system to represent uncertainty/variability as shown in **Exhibit 2-26**.

EXHIBIT 2-26. STACKED BAR EXAMPLE FIGURE



Each impact category analyzed shall have its own stacked bar chart when more than one impact category is considered. See **Section 4.0** for an example of how openLCA displays a contribution analysis as a stacked bar chart. For the purposes of this guidance, Pls shall generate stacked bar charts that are delineated by unit process, include only unit processes that contribute 10 percent or more to the total life cycle impacts, and graph no more than five product systems on one graph.

In addition to the chart(s), Pls shall report the quantitative results for each impact category in a table. Pls shall also calculate the ratio and percent change between the Proposed Product System(s) and the Comparison Product System(s) for each impact category and display the results in a table. The ratio shall be calculated as follows for each impact category:

$$\text{Ratio} = \frac{\text{Total Proposed Product System}}{\text{Total Comparison Product System}} \quad \text{EQUATION 2-4}$$

“Total” refers to the result for a given impact category. The percent change shall be calculated as follows for each impact category:

$$\text{Percent Change} = \frac{\text{Total Proposed Product System} - \text{Total Comparison Product System}}{\text{Total Comparison Product System}} \times 100 \quad \text{EQUATION 2-5}$$

Negative number results in the percent change calculation indicate an improvement over the Comparison Product System (i.e., a decrease in emissions). A positive number indicates an increase in emissions over the Comparison Product System. Results shall be reported in the report document outlined in **Section 6.0**.

## 2.4.2 UNCERTAINTY AND SENSITIVITY ANALYSIS

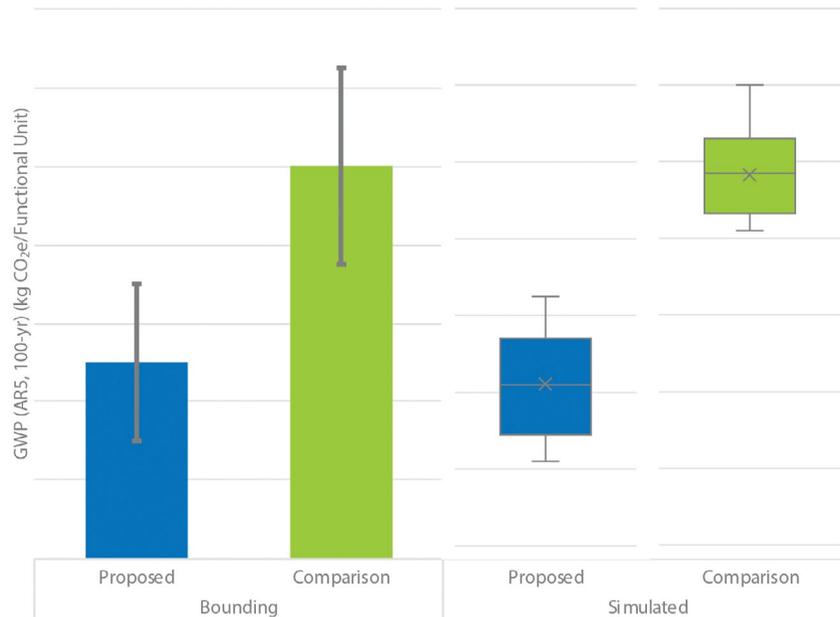
The parameters in **Exhibit 2-24** can be described in two groups: direct relationship between parameter value and life cycle GHG emissions (parameters A, C, and E) and inverse relationship between parameter value and life cycle GHG emissions (parameters B and D). Pls shall use parameters to model a minimum of three unique scenarios of the Proposed and Comparison Product Systems. These scenarios shall characterize the underlying uncertainty and variability and be defined as low-GWP, expected-GWP, and high-GWP (see **Section 3.5** for product system results graphing and sensitivity scenario nomenclature).

There are two ways in which Pls can conduct the uncertainty analysis. The first option is to create bounding scenarios. Those scenarios determine the values of the parameters that yield the highest and lowest GWP results. Note, these values may not correspond to the high and low values of the parameters as there can be both direct and inverse parameters as noted above. The high- and low-GWP scenarios pair parameter values accordingly to yield what are referred to as bounding results. The values represented by the bounding results are unlikely as they result in the pairing of all extreme parameter values together. However, this type of an analysis can be useful for a first-pass at interpreting a model’s sensitivity.

Alternatively, if Pls have enough information about the distribution of their model parameters (e.g., uniform, triangular, etc.), simulation approaches (e.g., Monte Carlo) can be utilized to refine the range of uncertainty in the GWP results. The differences between these two approaches for a model system are depicted in **Exhibit 2-27**. The bounding scenario shows the low, expected, and high GWP results. The expected scenario is presented as the height of the column and the low and high results are represented using error bars. The results of the bounding scenario do not ascribe any likelihood to the outcome. Alternatively, the simulated results generally show a tighter distribution and can be used to interpret likelihood. In this case the results are presented as a box and whisker plot.

The Pls shall also complete a sensitivity check as part of the interpretation phase. One common approach for the interpretation phase sensitivity check is a breakeven analysis. The purpose of the breakeven analysis is to determine the sensitivity of the results to key parameters. In a breakeven analysis, one or more parameters should be changed to a value until the results of the Proposed Product System and the Comparison Product System are equal. The interpretation of these results can be used to test the robustness of the study conclusions and point to any potential study limitations.

#### EXHIBIT 2-27. EXAMPLE OF DIFFERENT APPROACHES TO MODELING UNCERTAINTY



### 2.4.3 STUDY LIMITATIONS

Pls shall describe any data limitations with the model or data for both the Proposed and Comparison Product Systems. This discussion shall also include the effect on the interpretation of results.

### 2.4.4 STUDY CONCLUSIONS AND RECOMMENDATIONS

Pls shall discuss the key modeling parameters that influence the study results and document through sensitivity analysis the change in key impact categories that would alter the study conclusions, if applicable.

Pls shall provide a summary narrative of the LCA study conclusions based on the analysis of results, including sensitivity and uncertainty. Pls shall also report recommendations to improve the accuracy and reduce the uncertainty of the results.

### 2.4.5 CRITICAL REVIEW

US DOE's Carbon Utilization Program will serve the role of critical review for this process. Recommended text is suggested in the report template. If additional critical reviews are conducted prior to submission DOE, the names, affiliations, and contact information shall be documented for each external reviewer.

## 3.0 USING OPENLCA FOR CO2U LCA

openLCA is an open source LCA software platform. [24] openLCA makes it easier to include more inventory data, apply an impact assessment method, and include uncertainty and sensitivity parameters in an analysis than it would be in a spreadsheet model. NETL has created an openLCA database, referred to as the “**NETL CO2U openLCA LCI Database**,” that includes an example LCA and NETL unit processes. **Appendix A** provides instructions on where to download a free copy of the openLCA software and the **NETL CO2U LCI Database**. Details on accessing openLCA modeling support are also available in **Appendix A**.

This section covers the specific use of openLCA to produce an LCA for the U.S. DOE Carbon Utilization Program. Instructions and trainings on the basic mechanics and more general use of openLCA will be provided elsewhere. The openLCA website provides free resources such as manuals and presentation on [openLCA.org/learning](https://openLCA.org/learning). Additional trainings are also provided in the **NETL CO2U LCA Guidance Toolkit**, as seen in **Appendix A**. This section will only include CO2U-specific mechanics and the conventions necessary to ensure submissions are useful and consistent. The following sections will describe how to organize the database, utilize NETL-provided processes, build and run CO2U product systems and projects, and display and compare results.

### 3.1 DATABASE STRUCTURE AND ORGANIZATION

Included in the openLCA software is both the data storage and the ability to create new data and models. This means that submissions will include both the immediate work product (the product systems and results) via the **NETL CO2U LCA Report Template** and the database those work products are modeled within via their project-specific copy of the **NETL CO2U openLCA LCI Database**. To improve database management, the PIs shall strive for a well-organized and easy-to-navigate file structures in their database and adhere to the following methods for similar structures:

**Do not make changes to the existing folders or features inside the folders.** openLCA provides a set of flows and background data with the software downloads as well as impact assessment methods as a separate download (which is not necessary for the NETL analysis). The **NETL CO2U openLCA LCI Database** has been pre-populated to provide a project, product systems, and processes associated with an example system and comparison as well as unit processes for PIs use in a folder called “NETL Process Library.” Utilize any of this existing data, but do not change it in any way, including the location of the data in the database. The only exception to this rule is the electricity grid mixer, which is discussed further in **Section 3.3**. If changes to any of the existing data are necessary to create an alternative unit process, follow the instructions for creating duplicates, as discussed below.

**Duplicate data only as necessary.** Having duplicate data can clutter databases and should only be used if 1) the PIs are making a change to an existing dataset or 2) if the same data can be used in multiple places but needs to hold different parameters in the same product system. The reason to use duplicates in the case of (1) is to ensure the data can easily be reverted to the original version if necessary and so the NETL reviewers are aware of the changes being made. Case (2) can be necessary for technical reasons. For example, if the same product system requires one electricity grid mix as an input to a process and another electricity grid mix as makeup electricity for their CO<sub>2</sub> source. To do this, a duplicate of the “Generic Power Grid Mixer” unit process would be necessary to hold the second set of parameters.

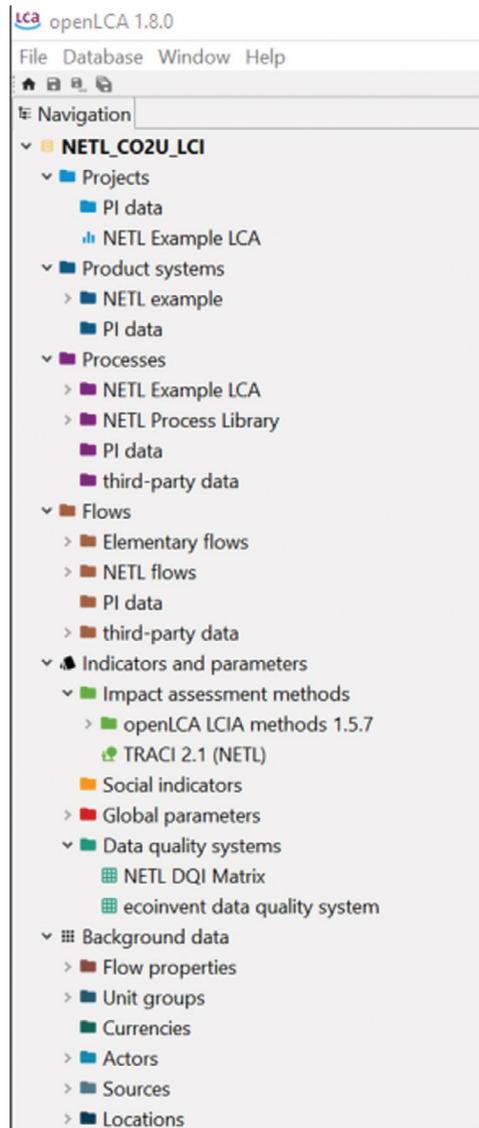
To make a duplicate, create a copy of the existing dataset, move the copy to a different folder, and add a concise description of the reason the duplicate was necessary. For the grid electricity example, this would mean copying the electricity grid mix unit process, moving it out of the “NETL Process Library” and add the exact grid mix (such as 2025 MRO) to the name of the process.

**Add new data in the “PI data” folders.** Add any newly generated or documented data to the dedicated “PI data” folders. There will be dedicated folders in the database labeled “PI data” in the Projects, Product systems, Processes, and Flows folders. New projects, product systems, and processes will be necessary for the analysis, and shall be added to the “PI Data” folders. Avoid creating new elementary flows, because the impact assessment methods will not assess newly-created flows. However, the “PI data” folder for intermediate flows is available for new product flows. If new datasets which are not a project, product system, process, or flow are needed, a new folder called “PI data” shall be created for them. For example, if a new data source is used for a process, a folder called “PI data” under the “Sources” folder shall be created in which to hold those sources.

**Add third-party data in the “Third-party data.”** Third-party data is any data entered into the database “as-is” from other data sources, such as the LCA Commons or the openLCA nexus. Data which third-parties generated, but were re-organized or used in calculations by the PIs to make into a unit process format manually, do not count as third-party data. For example, if a literature review was performed to find emissions factors and input it into a unit process, the resulting process would be added to the “PI data” folder. The original data source shall be recorded in the metadata of the process. Unit processes which had been purchased in a different LCA software and simply converted to openLCA would be considered third-party data.

Following these rules will create a file structure similar to that depicted in **Exhibit 3-1**.

### EXHIBIT 3-1. SUGGESTED PROCESS FOLDER STRUCTURE IN OPENLCA



## 3.2 BUILDING NEW UNIT PROCESSES

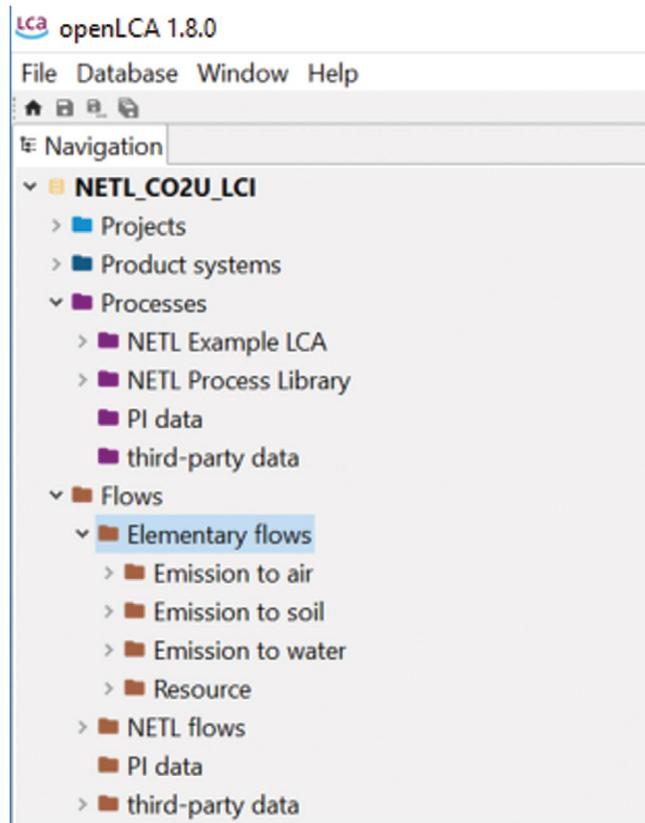
At least one new unit process – the CO2U process – will be needed to create the Proposed Product System. All newly created processes shall have as much documentation as possible in the metadata of the process. This includes, at minimum:

- General information
  - Name
  - Description
  - Location
  - Technology description
- Administrative information
  - Intended application
  - Data set owner
  - Data generator
  - Data documenter

If the process uses sources outside the Pls' organization, then the "Sources" section in "Modeling and validation" must include those sources.

openLCA has a comprehensive list of elementary flow names to use when building unit processes. The location of these elementary flows in the database is highlighted in **Exhibit 3-2**. It is important to use these existing elementary flows, because they are also used in the impact assessment methods that openLCA provides, which allows impacts to be calculated. Elementary flows that are not in the impact assessment methods will not have impacts calculated for them in the results.

**EXHIBIT 3-2. FLOWS AND FLOW FOLDER STRUCTURE IN THE NETL CO2U OPENLCA LCI DATABASE**



**Exhibit 3-3** is the proposed process for an algae example that produces the product of interest. In this case it is algae biodiesel. This process also creates other co-products including succinic acid, and protein (animal feed). The available emissions data for this process is CO<sub>2</sub> emissions.

## EXHIBIT 3-3. ALGAE BIODIESEL SYSTEM UNIT PROCESS IN THE NETL CO2U OPENLCA LCI DATABASE\*

Inputs									
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Description
Algae biomass	NETL flows	0.10505	kg		none				
carbon dioxide	NETL flows	net_CO2_input	kg		none		CO2 Source Ml...		
Diammonium Phosphate	NETL flows/Materials production	0.00180	kg		none		Diammonium Ml...		
Electricity	NETL flows/Energy carriers and tech...	elec_tot	kWh		none		Generic Power ...		
Ethanol, mass	NETL flows/Energy carriers and tech...	0.00317	kg		none		Ethanol-Lignoc...		
Heat	Resource/unspecified	0.18300	MJ		none				
Methanol	NETL flows/Energy carriers and tech...	0.00301	kg		none		Methanol from...		
Sulfuric acid, at plant - RNA	NETL flows/third-party data (examp...	0.00036	kg		none		Sulfuric acid, at...		
Urea	NETL flows/Materials production	0.00200	kg		none		Urea Production		
Water, unspecified natural origin, US	Resource/in water	5.05000	l		none				

Outputs									
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Description
Algae Biodiesel	NETL flows/Energy carriers and t...	1.00000	MJ		none				
Algae Protein	NETL flows/Materials production	0.04410	kg		none	<input type="checkbox"/>			
Carbon dioxide	Emission to air/unspecified	co2_pomd_em	kg		none				
Succinic Acid	NETL flows/Materials production	0.01230	kg		none	<input type="checkbox"/>			

\*This unit process is incomplete as it is missing providers for some of the inputs. This means that the upstream impact of these inputs will not be accounted for in the LCA. The example model provided in openLCA is for educational purposes only.

This Proposed Product System also includes several inputs. In this example, upstream unit processes are included for the production of these inputs. Several of the upstream inputs were omitted from this example for the sake of simplicity. For a complete LCA, all inputs that have upstream impacts shall be included in the LCA unless they meet cut-off criteria.

Any inputs or outputs which will be used in a sensitivity or uncertainty analysis shall have an associated parameter. This will make it possible to run sensitivity and uncertainty scenarios by simply changing parameters and re-calculating the product system. It will also make the use of projects possible, as discussed in **Section 3.5** If there are simple mathematical relationships between inputs and outputs, these shall be reflected in the relationships between input and dependent parameters. This will ensure that the sensitivity and uncertainty analysis will automatically capture those interdependencies. The parameters shall have short, descriptive names, but also a fuller description in the "Description column." All parameters must include descriptions which include, at minimum, the unit of the parameter. **Exhibit 3-4** depicts the parameters used in the example algae process.

EXHIBIT 3-4. PARAMETER SET-UP FOR EXAMPLE ALGAE PATHWAY

**Global parameters**

Name	Value	Uncertainty	Description
biodiesel_density	0.023989519	none	gram biodiesel/BTU
carbon_content	0.55	none	g C/g algae - carbon content of algae sp...
co2_pump_elec	3.04127157217367E-5	none	kWh/g CO2 - power required for pumpi...
CO2_recycle_rate	0.018118078	none	% - rate at which CO2 gets recycled thro...
CO2_to_SA	0.0543	none	kg/MJ biodiesel - carbon required for su...
CO2_util_eff	0.82	none	% - CO2 utilization efficiency at pond
electricity_in	0.101887128561765	none	kWh/MJ biodiesel - electricity input to de...

**Dependent parameters**

Name	Formula	Value	Description
CO2_input	carbon_content *44/12/CO2_util_eff	2.4593495934959355	g CO2 /g afdw algae - CO2 input to alga...
CO2_input_norm	CO2_input *4.4*1.05/1000/0.00105506*biodiesel_density	0.25834890504782304	kg/MJ biodiesel - CO2_input scaled up t...
CO2_pond_em	(1-CO2_util_eff)*CO2_input_norm	0.04650280290860816	kg CO2/MJ biodiesel CO2 lost at pond, ...
CO2_pump_en	CO2_input *co2_pump_elec *4.4*1.05	3.4555521021880595E-4	kWh/MJ biodiesel - energy required to p...
elec_tot	CO2_pump_en+electricity_in	0.10223268377198381	kWh/MJ biodiesel - total electricity input ...
net_CO2_input	CO2_input_norm*(1-CO2_recycle_rate)+CO2_to_SA	0.307968119434952	kg CO2/MJ biodiesel - total CO2 enterin...

Notice that the parameters that are used in the Inputs/Outputs in **Exhibit 3-3** do the following: “CO<sub>2</sub>\_pond\_em” determines the CO<sub>2</sub> emissions at the pond, “CO<sub>2</sub>\_pump\_en” determines the electricity requirement at the pond, and “net\_CO<sub>2</sub>\_input” determines how much CO<sub>2</sub> enters the system. All three of these inputs and outputs will now respond to any sensitivity or uncertainty used on the input parameters, such as the carbon content of the algae or CO<sub>2</sub> utilization efficiency. Other input parameters, such as “biodiesel\_density”, are not advisable to use for sensitivity because it would affect all inputs, outputs, and emissions in the process and those interdependencies are not reflected in the openLCA process. If the Pls wanted to create a sensitivity around the biodiesel density, it may be advisable to create an input parameter for every input and output in the system, utilize a third-party software, such as Microsoft Excel®, and paste in the resulting parameters into the openLCA process before calculating.

When the Proposed Product System produces multiple co-products, the Comparison Product System will need to have a unit processes that produces the same amount of all the co-products using the technologies that were determined in **Section 2.1** To provide the same service or function to society. The systems that make each co-product in the Comparison Product System example are not connected to each other, but for the purposes of LCA software modeling in openLCA, they must be connected in order for the software to calculate them as a single product system. To connect them, create a unit process that has inputs of each of the co-products and an output of one piece, as seen in **Exhibit 3-5**. The unit processes that create the co-products are then the “Providers” for this unit process.

## EXHIBIT 3-5. EXAMPLE PROCESS TO LINK CO-PRODUCTS IN THE COMPARISON PRODUCT SYSTEM

The screenshot shows the 'Inputs/Outputs: Algae Outputs' window in OpenLCA. It contains two tables: 'Inputs' and 'Outputs'.

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
Electricity [Electric power]	NETL database	1.17964	MJ		none		Generic ...		
Ethanol, energy, combusted	Energy carriers and technol...	1.00000	MJ		none		Ethanol ...		
Protein	Materials production/Othe...	0.04410	kg		none		Convert ...		
Succinic Acid	Materials production/Orga...	0.01230	kg		none		Succinic ...		

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Algae Equivalents	Materials production/Oth...	1.00000	Item(s)		none				

At the bottom of the window, there is a navigation bar with the following tabs: General information, Inputs/Outputs, Administrative information, Modeling and validation, Parameters, Allocation, and Social aspects.

Because of the complexities involved in calculating the makeup electricity, as described in **Section 2.1.5**, the CO<sub>2</sub> sources and makeup electricity will be automatically calculated if CO<sub>2</sub> input from the CO2U process and is included in the “CO<sub>2</sub> Source Switch” process as the provider. Then, the correct upstream profiles can link together automatically when the product system is created, as discussed in **Section 3.3**.

### 3.3 BUILDING PRODUCT SYSTEMS

In the “PI data” folder in “Product systems,” create a new product system and choose the appropriate reference process (**Exhibit 3-6**). Do the same for the Comparison Product System (**Exhibit 3-7**). Verify that all unit processes have the correct default providers and the “Only link default providers” option is selected. Then, the whole product system, including upstream CO<sub>2</sub> sources and makeup electricity, will automatically connect correctly. Double-check these connections in the model graph.

**Exhibit 3-6** also shows how conversion unit processes can be used. For example, energy to mass and mass to energy unit processes are used when one wants to connect an *energy flow* (MJ) to a mass flow (kg) and vice versa. Within **Exhibit 3-6**, Algae Biodiesel is converted from mass to energy units using this technique. Alternatively, unit processes created by the PIs can be converted in the data collection and unit process development phases, so the connecting intermediate flows can be the same.

EXHIBIT 3-6. EXAMPLE PROPOSED PRODUCT SYSTEM IN OPENLCA

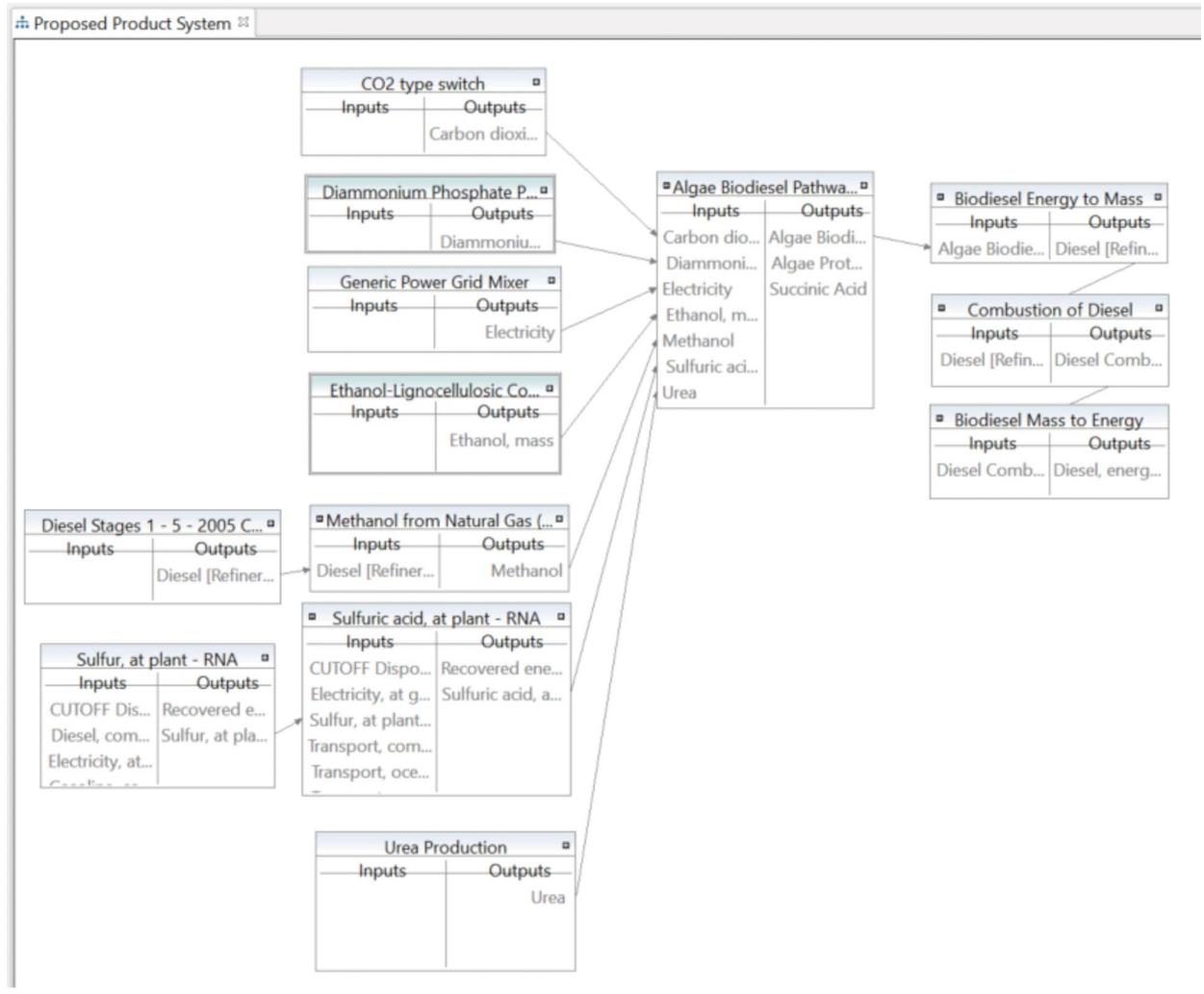
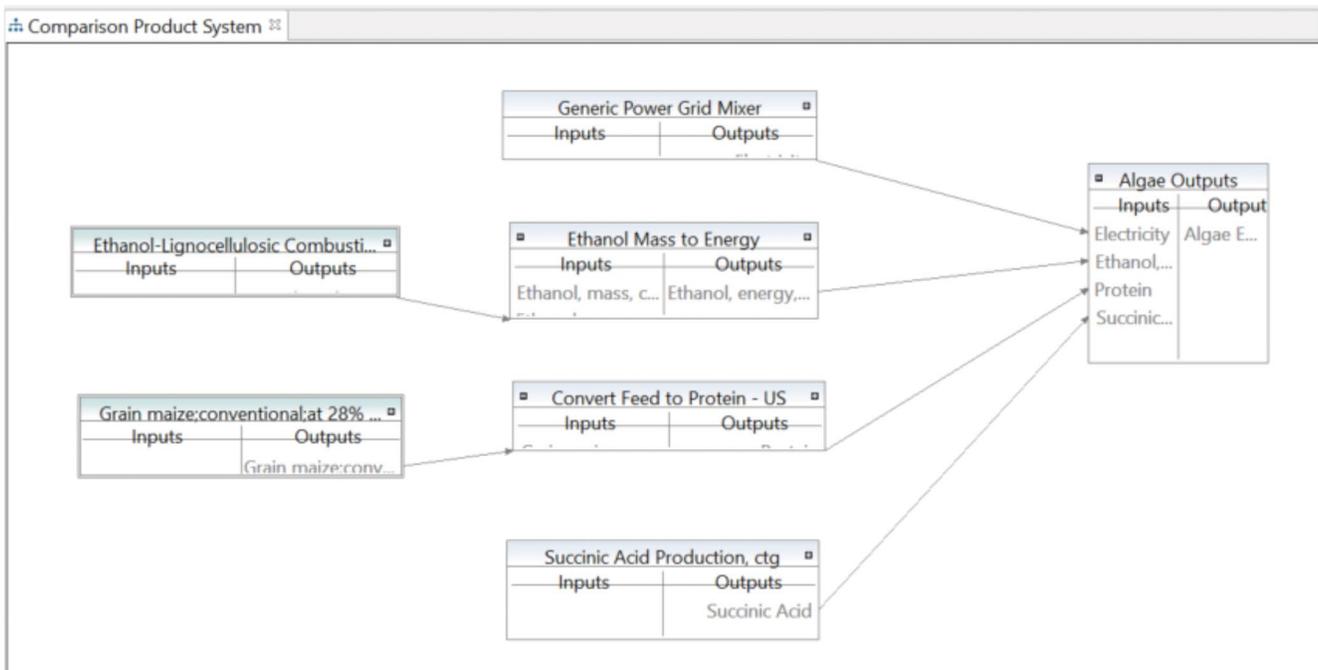


EXHIBIT 3-7. EXAMPLE COMPARISON PRODUCT SYSTEM IN OPENLCA



### 3.4 PERFORMING A PRODUCT SYSTEM ANALYSIS

After creating product systems in openLCA for the NETL default product system and any alternative product systems considered in the study, open the product system in an editor window. Check the “Model graph” and “Parameters” tabs to ensure the information in the product system is correct. On the “General information” tab, click the “Calculate” button. In the ensuing pop-up window,

- For the Impact assessment option, select the *TRACI 2.1 (NETL)* option
- For the Calculation type, select the “Analysis” button
- Then select “Finish.”

Only select an allocation method or normalization and weighting set if necessary for secondary analysis – the analysis required in this document does not include either. Choosing these options without having previously modeled these methods can result in errors and null values that should not be null. See **Exhibit 3-8** for available choices in the pop-up window.

EXHIBIT 3-8. POP-UP WINDOW CHOICES FOR PRODUCT SYSTEMS IN OPENLCA

The resulting analysis will have several tabs full of important information and easy-to-use automatic tables and graphs useful for exploring and understanding the modeled product systems. Assess the Inventory results, Impact results, Process results, and Sankey diagram to check for any surprising results which could point to errors in the model. The contribution tree is used by the **NETL CO2U LCA openLCA Results Contribution Tool** to generate figures for the **NETL CO2U LCA Report Template**.

### 3.5 BUILDING PROJECTS

Projects can be useful tools for quick comparisons of product systems. This is especially useful for sensitivity and uncertainty because of the ability to change parameters and automatically display the results side-by-side.

In the “PI data” folder in “Projects,” create a new project and name it after the PIs CO2U project. Select TRACI 2.1 (NETL) as the impact category. Add the Proposed and Comparison Product Systems to the “Compared product systems” section. For sensitivity and uncertainty results, add multiples of the same product system and change the parameters of interest in the “Parameters” section of the project editor. Move to the “Report sections” tab and select the visualizations needed in the resulting report. Select the “Report” button on the “Project setup” tab to generate results (**Exhibit 3-9**).

## EXHIBIT 3-9. SETUP FOR RESULTS GENERATION IN OPENLCA

**Project setup: NETL Example LCA**

**General information**

Name: NETL Example LCA

Description:

Version: 00.00.015

UUID: e9479dfc-dd63-4047-848d-a3a35f3cef4b

Last change: 2019-03-26T15:35:09-0400

**LCIA Method**

LCIA Method: TRACI 2.1 (NETL)

Normalization and weighting set:

Impact category	Display	Label in report	Description
Global Warming Potential [100 yr] - TRACI 2.1, modified	<input checked="" type="checkbox"/>	Global Warming Potential [100 yr] - TRACI 2.1, ...	
Particulate Matter Formation Potential - TRACI 2.1, modified	<input checked="" type="checkbox"/>	Particulate Matter Formation Potential - TRACI 2...	
Eutrophication Potential - TRACI 2.1	<input checked="" type="checkbox"/>	Eutrophication Potential - TRACI 2.1	
Ozone Depletion Potential - TRACI 2.1	<input checked="" type="checkbox"/>	Ozone Depletion Potential - TRACI 2.1	

**Compared product systems**

Name	Product system	Display	Allocation method	Flow	Amount	Unit	Description
Option2	Comparison Product System	<input checked="" type="checkbox"/>	None	Algae Equivalents	1.0	Item(s)	
Proposed Product System	Proposed Product System	<input checked="" type="checkbox"/>	None	Diesel, energy, combusted	1.0	MJ	

**Parameters**

Parameter	Context	Label in report	Description	Option2	Proposed Product System

**Process contributions**

Process	Label in report	Description
Ethanol-Lignocellulosic Combustion-Corn Stover with combustion	Ethanol-Lignocellulosic Combustion-Corn Stover with combustion	This system process was created in GaBi software using the NETL ethanol profile detailed in "Life Cy...

The tables generated in the report viewer can be useful for pasting into the **NETL CO2U LCA Report Template**. Additionally, the automated results are useful for exploring the model, and may show obvious errors in the model. For example, in the Product system named “Proposed, low CO<sub>2</sub>\_rec”, the parameter representing the CO<sub>2</sub> recycle rate at the CO2U project was changed to be lower than the default. This parameter change would require more CO<sub>2</sub> input, and therefore more electricity and everything upstream of CO<sub>2</sub> production. Therefore, if the GHG impacts results are lower than the default product system, then the model should be checked for errors.

### 3.6 DISPLAYING AND COMPARING RESULTS

By creating a project and using the report viewer tool, several of the tables for the **NETL CO2U LCA Report Template** can be created using the reports viewer tool. A parameter sensitivity scenarios description table can be created using the “Project Variants” option in the reports viewer. Impact assessment results tables can be created using the “Selected LCIA Categories” table in the reports viewer. Impact assessment results figures (graphs) can be created using the **NETL CO2U LCA openLCA Results Contribution Tool**. See **Section 4.0** for further instructions on using the results contribution tool.

## 4.0 USING THE CONTRIBUTION TREE EXCEL TOOL TO TRANSLATE OPENLCA RESULTS INTO THE REQUIRED GRAPHS

The **NETL CO2U LCA openLCA Results Contribution Tool** provides an automated template for generating bar charts that represent the primary unit process contributors (e.g., >10 percent contribution) to each impact category with totals and uncertainty bars for each product system. These graphs meet the reporting requirements for the Contribution Analysis results in the **NETL CO2U LCA Report Template**. The following sections describe how to use the **NETL CO2U LCA openLCA Results Contribution Tool** with the openLCA model to streamline results interpretation and reporting.

### 4.1 COPYING SHEET 1 FOR EACH SCENARIO

In the **NETL CO2U LCA openLCA Results Contribution Tool**, there are eight sheets. The first sheet, “Comparison,” provides the primary sheet for identifying the product systems and their accompanying uncertainty/variability scenarios, within which the tables and graphs comparing the different product systems will be compiled.

The second sheet, labeled “Keys,” does not need to be edited, unless additional impact categories other than the NETL-recommended impact categories are modeled, in which case the table in **Cells A1:C8** can be edited to describe those impact categories before any calculations are done. The edited impact category table can be lengthened to row 40 if necessary. Otherwise, do not edit the “Keys” sheet.

The other six sheets leave space for analysis results. Each of these sheets will contain the information from a single product system. The minimum number of product systems required for the default NETL analysis is an expected, low, and high version of the default Proposed Product System and an expected, low, and high version of the default Comparison Product System. A sheet for each of these product systems is included in the tool already with an existing naming system. The default Proposed Product System with expected values is labeled “Prop-A-Exp”, which is short for “Proposed – A – Expected.” The sheet named “Prop-A-Low” is meant for the default product system with low values for the uncertainty analysis. “Comp” is short for “Comparison,” and the three sheets with “Comp” in the name follow the same pattern. For any alternative product systems, sheets will need to be added and renamed following the same naming system, but with a different letter to represent a different alternative. For example, the first alternative Proposed Product System with expected values would be named “Prob-B-Exp.” The corresponding Comparison Product System results would then be pasted onto a sheet named “Comp-B-Exp.” Any alternative product systems that have a different full functional unit than the default scenario will have to be presented on a separate graph, and therefore using a different copy of the **NETL CO2U openLCA Results Contribution Tool**.

To create sheets for alternative product systems, right click on the tab at the bottom of the sheet and use the “Move or Copy...” tool to create a copy of an existing results sheet and then rename it following the same naming convention. Note: there are numerous hidden columns in these sheets and their location in the sheet are important to the macros embedded in the template. Therefore, copy the entire sheet, and do not at any point delete any columns. To create a more user-friendly view, hide columns, freeze panes, or otherwise change the view, but do not delete or move columns.

### 4.2 MOVING THE CONTRIBUTION TREE TO THE EXCEL TEMPLATE

After performing a product system analysis, as described in **Section 3.4**, the product system analysis will create a new editing window in the **NETL CO2U openLCA LCI Database** with eight tabs including analysis results:

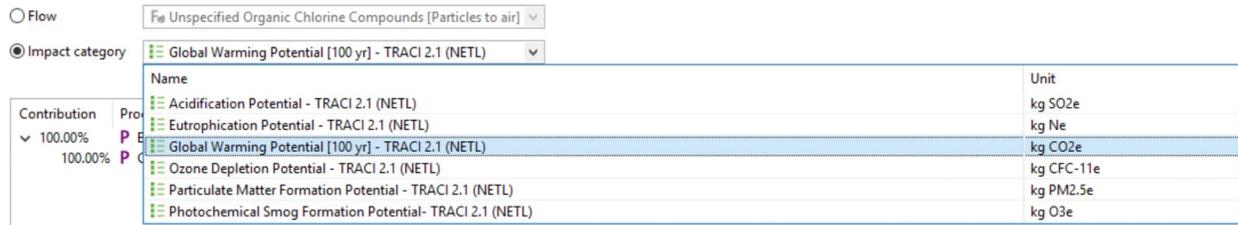
1. General information
2. Inventory results
3. Impact analysis
4. Process results
5. Contribution tree
6. Grouping
7. Locations
8. Sankey diagram

Note, if not all of the tabs listed below are visible in openLCA, an impact assessment method may not have been selected in the pop-up window when creating the product system. Additionally, other tabs may appear that could be the result of selecting an allocation method, or normalization and weighting method. Allocation, normalization, and weighting shall not be used in the default comparative analysis provided to NETL (i.e., Prop-A and Comp-A product systems).

All eight tabs in the openLCA analysis have important information and easy-to-use automatic tables and graphs useful for exploring and understanding product system life cycle results. For this template, however, only the “Contribution tree” tab is necessary to create the required results graphs.

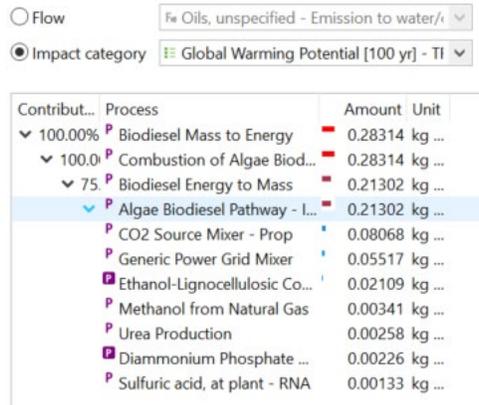
On the contribution tree in openLCA, select the “Impact category” button instead of the “Flow” button. Then, select the impact category of interest, as in **Exhibit 4-1**.

**EXHIBIT 4-1. IMPACT CATEGORY SELECTION ON THE CONTRIBUTION TREE TAB OF PRODUCT SYSTEM ANALYSIS RESULTS.**



Next, go to the contribution tree, and click on the arrows to the left of each row to expand the contribution tree, as in **Exhibit 4-2**.

**EXHIBIT 4-2. EXPAND THE CONTRIBUTION TREE USING THE ARROW BUTTONS TO THE LEFT**



After the Contribution Tree has been expanded, use ctrl+a (or cmd+a for Mac computers) to select the entire tree. Then right click to select “Copy” to copy the entire expanded tree to your clipboard (Note: the ctrl+c keyboard shortcut option does not always work within the editing windows in openLCA).

Paste the Contribution Tree from this scenario into **Cell A1** in the matching product system scenario sheet in the Excel template.

Repeat these copy-paste actions for each impact category, pasting the tree into the next blank row in the same sheet. For example, if your first tree was 27 rows long, the next tree (containing the information from the next impact category) would be pasted into **Cell A28**.

Then repeat all of these actions for each scenario in their matching sheets in the **NETL CO2U LCA openLCA Results Contribution Tool**.

## 4.3 CALCULATING RESULTS

Click on the “Calculate!” Button on the “Comparison” sheet. This will create calculations on the scenario sheets. It will also populate the “Keys” sheet with a list of sheets/product systems available to be graphed.

## 4.4 DETERMINING THE CONTENTS OF THE GRAPH

In the table from **Cells A1:D9** (max) on the “Comparison” sheet, create a list of product systems to be compared. In **Column A**, give the product system a full name to be displayed in the graph. In **Column B**, choose the sheet name that corresponds to that product system from the dropdown list of sheets. The dropdown list will prevent misspellings that will cause the embedded macros to not work.

In **Columns C** and **Columns D**, choose the sheet names that represent the high and low uncertainty scenarios for the product system described in **Column A**.

Next, in the table in **Cells A11:A30** (max), choose the impact categories to graph. Select “All” to automatically fill out the list with all available impact categories listed in the “Keys” sheet.

## 4.5 GRAPHING

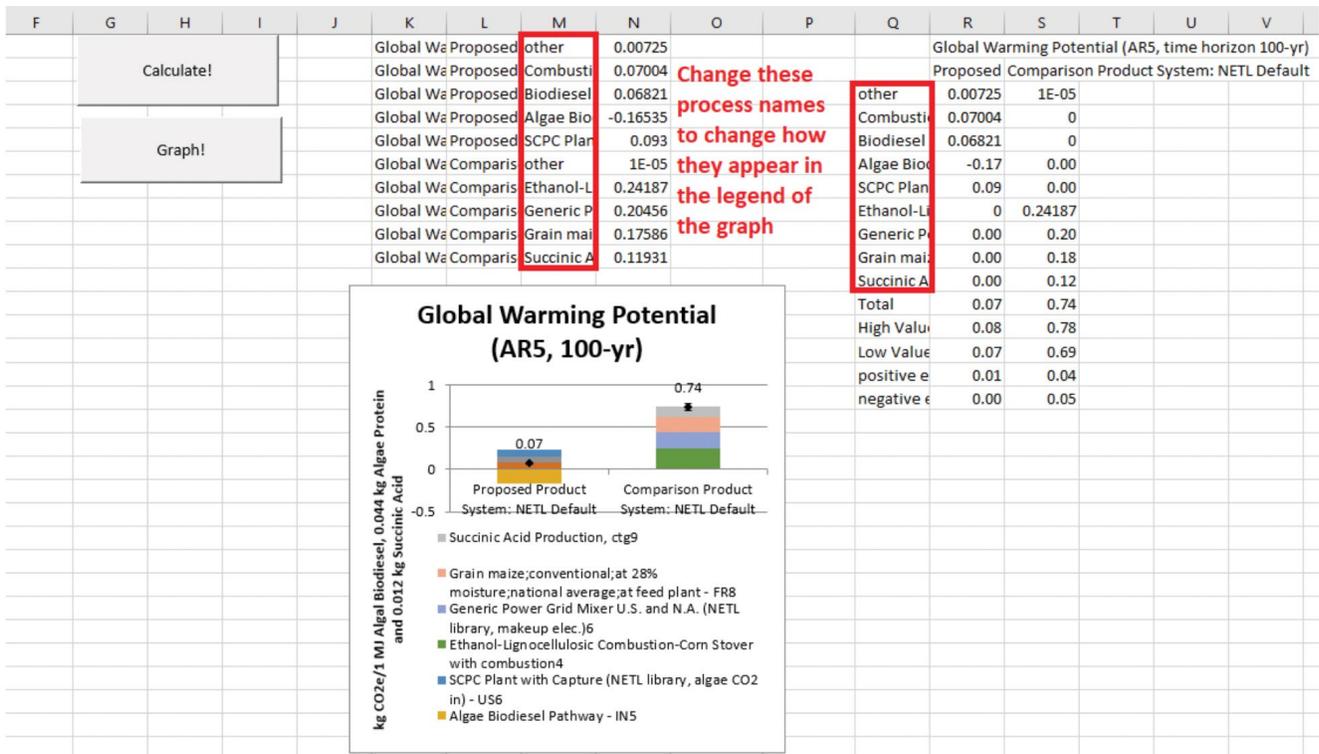
Click on the “Graph!” Button on the “Comparison” sheet. This will first ask to fill in the functional unit on which the product systems are being compared (for example, “1 MJ Algal Biodiesel” or “1 MJ Algal Biodiesel, 0.044 kg Algae Protein and 0.012 kg Succinic Acid”) This exact text will appear as part of the y-axis label of the resulting graph, so it should match the short functional unit determined in **Section 2.1** exactly.

## 4.6 CLEANING UP THE UNIT PROCESS NAMES IN THE GRAPH

The unit process names that automatically appear in the graph will be the unit process names in the openLCA model plus a number appended to the end. The unit process names in openLCA are often lengthier and more specific than they need to be in the graph. They also do not contain the context of the unit process’s place in the product system because they are meant to be reusable. For example, the unit process named “Generic Power Grid Mixer” in the database could be renamed “Electricity for Steam” to be more concise and differentiate it from other electricity uses. The numbers appended at the end of the unit process name represent the row it occupies in the product system sheet. Thus, if a unit process is used repeatedly (and it would therefore appear in the contribution tree multiple times), and one wants to understand what it is being used for, it can be identified in the contribution tree using the row number. **Appendix F** provides additional details on the elements of the contribution tree and the underlying math.

To change the names of the unit process, change the text in the cells in the table used for graphing and in the table of data feeding it. The data which feeds the graph is located just to the left of the table, sometimes underneath the graph. These locations are highlighted in **Exhibit 4-3**.

EXHIBIT 4-3. LOCATION OF PROCESS NAMES TO BE CHANGED



The completed graphs will quickly and clearly display the largest contributions to the product systems as well as a representation of the product system uncertainty. This, in addition to the results tools that are part of the openLCA software, will help to further understand the impacts of the product systems and check for potential errors in the model. If changes are made to the product systems in openLCA, re-run the analysis, paste the new contribution trees into the tool again and run the calculation and graphing tools again. Once the model has been checked for errors and the study data quality objectives have been met, these graphs shall be copied and pasted into the **NETL CO2U LCA Report Template** as part of the study results interpretation section.

# 5.0 USING THE NETL CO2U LCA DOCUMENTATION SPREADSHEET FOR DOCUMENTATION

This section provides guidance on using the **NETL CO2U LCA Documentation Spreadsheet** to provide unit process and life cycle system documentation when the spreadsheet model option is used (not openLCA), or when the openLCA software/database or other third-party LCA software/database are used but not provided for public release as part of the project's Final Scientific/Technical Report. See **Section 1.5** for details on modeling options and required methods for study transparency.

## 5.1 OVERVIEW

An **NETL CO2U LCA Documentation Spreadsheet** shall be completed for each Product System. The **NETL CO2U LCA Documentation Spreadsheet** includes a “Product System Overview” worksheet, “UP Template” worksheet, “NETL Unit Process Data” worksheet, and “GWP Impact Factors” worksheet. One “Product System Overview” worksheet shall be completed for each **NETL CO2U LCA Documentation Spreadsheet** completed. The “UP Template” worksheet is for documenting each unit process in the Product System that is not an accessible, third-party unit process. For each unit process, a copy of a blank UP Template shall be made and completed. The “NETL Unit Process Data” worksheet is the NETL unit process data that Pls should use and is also available in openLCA. This worksheet should not be modified; it is a data repository for PI use. The “GWP Impact Factors” worksheet is a table of GWP factors that Pls shall use in their analyses and is also available in openLCA. This worksheet should not be modified; it is a data repository for PI use.

## 5.2 PRODUCT SYSTEM OVERVIEW WORKSHEETS

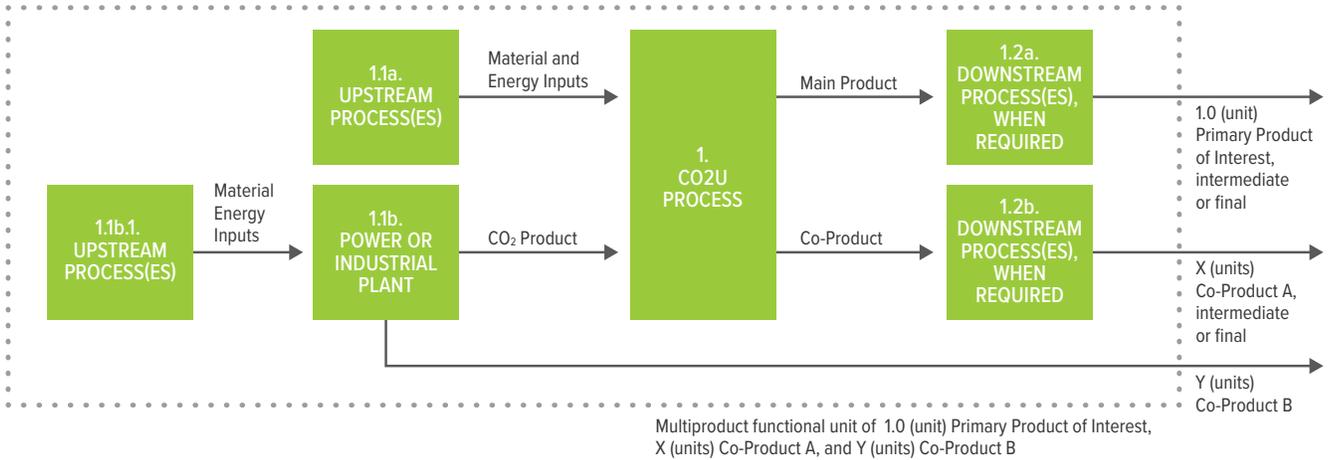
Pls shall complete the “Product System Overview” worksheet for the Product System covered in the **NETL CO2U LCA Documentation Spreadsheet**. Each Product System should have its own **NETL CO2U LCA Documentation Spreadsheet**. In **Cell A12**, indicate whether this spreadsheet represents a Proposed Product System or Comparison Product System. In **Cell A15**, indicate what the Product System identifier, shorthand, is for the system (e.g., PROP-A, PROP-B, COMP-A, COMP-B). In **Cell A18** provide a brief description of the Product System being document in the workbook. See **Exhibit 5-1** for a screenshot of the first half of the “Product System Overview” worksheet. The worksheet is partially completed with example text.

EXHIBIT 5-1. “PRODUCT SYSTEM OVERVIEW” WORKSHEET – PART I

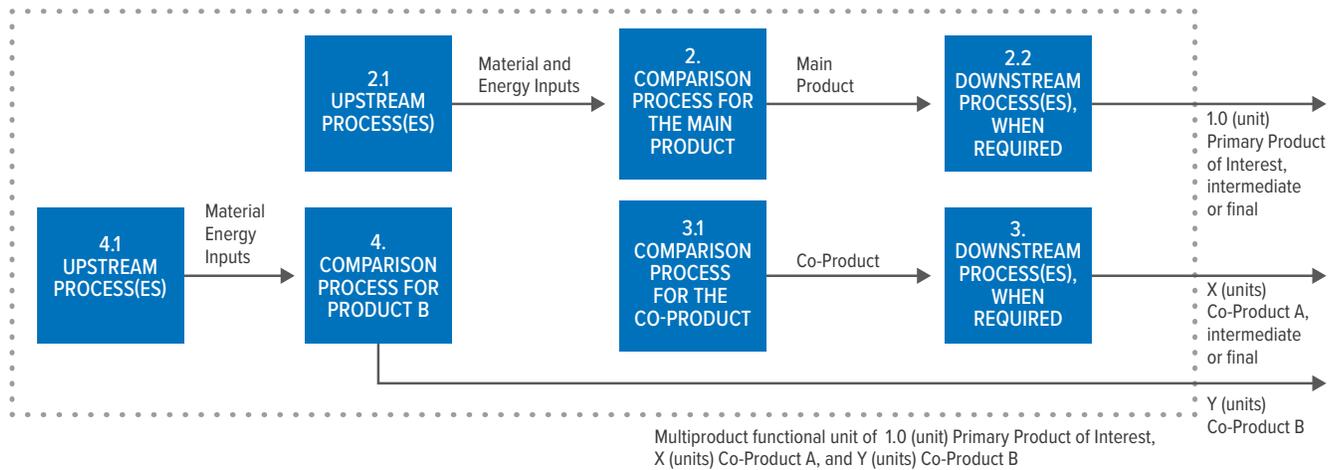
	A	B	C	D	E	F	G	H	I	J	
1	<b>Note About This File</b>										
2	This NETL CO2U LCA LCA Documentation Spreadsheet is a companion to the NETL CO2U LCA Guidance Document. Please see the NETL CO2U LCA Guidance Document for additional instructions, information, and abbreviations.										
3	This file is primarily for documenting unit processes and modeling structure when openLCA is not used. See the NETL CO2U LCA Guidance Document for instructions on where to document results.										
4											
5											
6	<b>Key</b>										
7	Fields marked in orange are areas for data entry										
8											
9											
10	<b>Numbered Diagram</b>										
11	Is this diagram for a Proposed Product System or Comparison Product System?										
12	Proposed Product System										
13											
14	What is the Product System identifier (e.g., PROP-A, PROP-B, COMP-A, COMP-B)?										
15	No										
16											
17	Provide a brief description below of the Product System being documented.										
18											
19											
20											
21	insert a unit process (UP) diagram for the Product System below. include a unique number for each UP for tracking purposes. Numbers should not be reused in other diagrams in this document.										
22	Add additional space below as necessary to fit diagram										
23											
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In **Cell A24**, Pls shall insert a unit process diagram that includes all of the unit processes used in Product System and shall use a name and unique number to label each unit process. See **Exhibit 5-2** and **Exhibit 5-3** for an example numbered diagram. In this numbering system, the *reference unit process* is the starting number for the group of connected *unit processes*. The Pls may use a simpler numbering system than what is used in **Exhibit 5-2** and **Exhibit 5-3**, including starting with the number one on the leftmost unit process and increasing the numbers to the right and down. Every unit process in the **NETL CO2U LCA Documentation Spreadsheet** shall have a unique number identifier.

**EXHIBIT 5-2. EXAMPLE NUMBERING SYSTEM FOR UNIT PROCESSES (PROPOSED PRODUCT SYSTEM)**



**EXHIBIT 5-3. EXAMPLE NUMBERING SYSTEM FOR UNIT PROCESSES (COMPARISON PRODUCT SYSTEM)**



In the table starting in **Cell A52**, Pls shall document each unit process that appears in the diagram by noting each flow in that unit process that is connected to a receiving unit process. The very last UP(s) in the chain shall also be documented, but they will not have any receiving flows. **Column A** in the table is the number identifier for the source unit process that the Pls are using, as it appears in the diagram. **Column B** is the name of the source unit process as it appears in the diagram. **Column C** is the citation for the source unit process. The citation should make it clear whether the unit process is a third-party unit process or a PI-developed unit process. **Column D** is the flow name for the flow that connects the source unit process to the receiving unit process. **Column E**, **Column F**, and **Column G** are the “Low”, “Expected”, and “High” flow values. Uncertainty analysis is required for each Product System modeled, however, not every tracked flow is required to have uncertainty characterized in the model. Therefore, it is expected that **Column E** and **Column G** may or may not have reported flow values, while **Column F** must always have a reported flow value. **Column G** is the optional “High” flow value when using uncertainty to bracket the “Expected” value. **Column H** is the units used for the flow value. **Column I** is the number assigned to the receiving unit process that receives the flow from the source unit process. **Column J** is the name of the unit process receiving the flow from the source unit process. **Column K** is reserved for any comments the Pls want to include about the table. See **Exhibit 5-4** for a screenshot of the second half of the “Product System Overview” worksheet with the table. The table is partially completed with example text.

EXHIBIT 5-4. “PRODUCT SYSTEM OVERVIEW” WORKSHEET – PART II

Source UP Number	Source UP Name	Source UP Citation	Flow Name	Low	Expected	High	Units	Receiving UP Number	Receiving UP Name	Comments
(PROP-A)1.	UP Name		Wastewater	0.00E+00	5.00E+01	0.00E+00	kg	(PROP-A)1.2.	Wastewater Treatm	This flow comes from the reference unit process, so the flow amount is 5.00+01 kg wastewater/kg main co-product x 1.00+00 kg main co-product = 5.00+01 kg wastewater
add additional rows as necessary										

5.3 UP TEMPLATE WORKSHEET

Pls shall complete a “UP Template” worksheet for each unit process and name the worksheet by the Product System and unit process number from the diagram worksheet. The Pls shall make a copy of the template and change the worksheet name to the Product System and unit process number. The **NETL CO2U LCA Documentation Spreadsheet** includes an example UP worksheet (“(PROP-A)1. UP Name”) that is populated with example data.

**Exhibit 5-5** is a screenshot of the first part of the “UP Template” worksheet. **Cell A13** is the unit process diagram number for the unit process as it appears in the diagram in the “Product System Overview” worksheet. **Cell A16** is the unit process name as it appears in the “Product System Overview” diagram.

EXHIBIT 5-5. “UP TEMPLATE” WORKSHEET – PART I

<b>Note About This File</b>																																																																																																		
This NETL CO2U LCA LCA Documentation Spreadsheet is a companion to the NETL CO2U LCA Guidance Document. Please see the NETL CO2U LCA Guidance Document for additional instructions, information, and abbreviations.																																																																																																		
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Unit process name:																																																																																																		
Unit process type (Operational, Construction, or Transportation):																																																																																																		
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**Cell A19** is the unit process type. There are three main types of unit processes that can be developed: operational, construction, and transportation. Operational unit processes are ongoing processes that have continuous inputs and outputs. This includes things like manufacturing, farming, mining, or waste processing, where the inputs are transformed to create different outputs. The reference flow in an operational unit process is usually measured in mass, volume, or energy; but also sometimes includes discrete units (pieces). Construction unit processes consist of a one-time effort to create pieces of equipment or infrastructure that will be used in an operational or transportation unit process, or another construction unit process. Construction unit process reference flows are usually measured as one discrete unit with the impact eventually divided by the lifetime of the constructed product. Transportation unit processes quantify the impact of moving an input from one location to another. The reference flow is usually measured in mass, volume, or pieces delivered over a defined distance.

**Cell A22** is where the PIs describe this unit process. The description shall include what the unit process does and what the important flows are. **Row 28** is for documenting the reported data boundary or denominator of the original data for the unit process. For operational unit processes, this is typically a year of operations. For construction unit processes this is usually the lifetime of the constructed item. For transportation unit processes, this is usually the distance traveled. In cases where the data is already normalized to the functional unit, enter the number 1 in **Cell B28**.

**Exhibit 5-6** is the second part of the “UP Template” worksheet. **Row 33** is for documenting the original data that will represent the reference flow for the unit process. **Row 38** and beyond is for documenting the original data that will represent the inputs and outputs of the unit process. Cells in orange are for data entry. Cells in blue are automatic calculations and should not be changed by the PIs.

**EXHIBIT 5-6. “UP TEMPLATE” WORKSHEET – PART II**

The screenshot shows a detailed spreadsheet template for documenting unit processes. It is organized into three main sections: Reference Flow (rows 30-34), Inputs and Outputs (rows 35-56), and Non-Consumable Input Flows (rows 57-66). Each section has a header row (e.g., 30, 35, 57) and a data table with columns for 'Amount per Reported Data Boundary', 'Amount per Factor', and 'Amount per Reference Flow'. Each of these columns is further divided into 'Low', 'Expected', and 'High' values, followed by 'Units'. The 'Inputs and Outputs' section also includes columns for 'Tracked Flows', 'Carbon Content (%)', and 'Mass Carbon Input'. The spreadsheet uses color-coding: orange for data entry cells and blue for automatic calculation cells. At the bottom, there are tabs for 'Product System Overview', '(PRDP-A)1. UP Name', 'UP Template', 'NETL Unit Process Data', and 'GWP Impact Factors'.

The inputs and outputs in the unit process template are separated by type. See **Section 2.2.2.1** for definitions of “inputs”, “outputs”, “reference flow”, and “non-consumables” as they appear in the worksheet. “Energy Input Flows” are input flows that are used for energy-only and are not material feedstocks. For example, natural gas can be both an energy source or a feedstock. Natural gas input that is only used for energy should be included in this section. Energy sources that are internal such as steam and onsite electricity generation should not be considered flows coming into the system. In the case of steam, water and fuel could be considered the incoming flows; for onsite electricity, feedstock fuels would be considered the incoming flow. If onsite electricity is coming from a renewable source, the originating source of energy (i.e., wind or solar radiation) does not need to specify the quantity of the input flow. Renewable energy inputs from wind, solar radiation, and kinetic hydraulic energy (hydropower) are managed as elementary flow inputs to the unit process and system boundary. Other renewable energy sources, such as, biomass must be quantified as an input flow. This does not mean, however, that there are no other flows into a renewable energy system that need to be tracked (e.g., construction of wind turbines), just the source of energy (i.e., wind) does not need to be tracked.

“Material Input Flows” are consumable input flows that are not used for energy. “Non-Consumable Input Flows” includes things like machines and catalysts. They are not consumed or transformed in the process, but may be tracked flows for upstream manufacturing impacts or downstream use/waste processing. Non-consumables should not be included in the carbon balance, and the amount per factor in **Column F** through **Column G** is independent from the amount per factor of consumables and should be reported by the PIs.

“Saleable Output Flows” are valuable materials that are the primary product of interest and other co-products. “GHG emission flows” are any air emissions with a GWP value. “Remaining Output Flows” are any output flows not included in the other categories. For example, this could include emission flows that are not GHGs, such as non-GHG air emissions, water pollutants, or solid waste.

**Column A** through **Column E** are where the input and output flows are reported. **Column A** is the name of the flow, **Column B** through **Column D** are the flow values. **Column E** is for the flow units and should not include the data boundary (denominator) units from **Row 28**.

**Column F** through **Column H** normalizes the flows in **Column B** through **Column D** to the data boundary. **Column I** documents the units.

**Column J** through **Column L** normalizes all the inputs and outputs to the reference flow. **Column M** documents the units.

In **Column N**, Pls shall place an “X” in cells where the flows are tracked, meaning that a flow is connected to an upstream or downstream unit process. Flows that are not generally tracked include emissions directly to the environment, flows that meet the cut-off criteria, and flows where the impact of their source has been satisfied (e.g., a cradle-to-gate natural gas unit process includes the impact of the extraction of the natural gas from the ground).

**Exhibit 5-7** is the third part of the “UP Template” worksheet. **Column O** through **Column Q** are for calculating the carbon balance in **Cell P114** in the template. All consumable input and output flows should conserve mass; no matter should be lost in the system. The carbon balance is a way to ensure that all the carbon coming into the system leaves the system, although it can be transformed (e.g., from natural gas as a material input to CH<sub>4</sub> and CO<sub>2</sub> as an emissions outputs).

**Column R** is for citing references or explaining anything in the unit process.

**EXHIBIT 5-7. “UP TEMPLATE” WORKSHEET – PART III**

	K	L	M	N	O	P	Q	R
31	per Reference Flow							
32	Expected	High	Units					
33	0.00E+00	0.00E+00	/					
34								
35								
36	per Reference Flow			<b>Tracked Flows:</b>	<b>Carbon Balancing ("Expected" only):</b>			
37	Expected	High	Units	Flows that Link to Other UPs	Carbon Content (%)	Mass Carbon Input	Units	Comments/References
38	0.00E+00	0.00E+00	Grid Electricity/		N/A	N/A	N/A	
39	0.00E+00	0.00E+00	/			0.00E+00	/	
40	0.00E+00	0.00E+00	/			0.00E+00	/	
41	0.00E+00	0.00E+00	/			0.00E+00	/	
42	0.00E+00	0.00E+00	/			0.00E+00	/	
43	0.00E+00	0.00E+00	/			0.00E+00	/	
44								
45								
46								
47	per Reference Flow							
48	Expected	High	Units	Flows that Link to Other UPs	Carbon Content (%)	Mass Carbon Input	Units	Comments/References
49	0.00E+00	0.00E+00	/			0.00E+00	/	
50	0.00E+00	0.00E+00	/			0.00E+00	/	
51	0.00E+00	0.00E+00	/			0.00E+00	/	
52	0.00E+00	0.00E+00	/			0.00E+00	/	
53	0.00E+00	0.00E+00	/			0.00E+00	/	
54	0.00E+00	0.00E+00	/			0.00E+00	/	
55								
56								
57								
58	per Reference Flow							
59	Expected	High	Units	Flows that Link to Other UPs	Carbon Content (%)	Mass Carbon Input	Units	Comments/References
60	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
61	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
62	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
63	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
64	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
65	0.00E+00	0.00E+00	/		N/A	N/A	N/A	
66								
67								
68								
69	per Reference Flow							
70	Expected	High	Units	Flows that Link to Other UPs	Carbon Content (%)	Mass Carbon Input	Units	Comments/References
71	0.00E+00	0.00E+00	/			0.00E+00	/	
72	0.00E+00	0.00E+00	/			0.00E+00	/	

## 5.4 SCREENSHOTS AND ACCOMPANYING FILES

In addition to the worksheets discussed above, the Pls may include extra worksheets with screenshots from the LCA software used. If including screenshot worksheets, the Pls shall label them appropriately and include an explanation of the screenshot. Pls may also include other accompanying support files with their submission.

## 5.5 NETL UNIT PROCESS DATA AND GWP IMPACT FACTORS WORKSHEETS

PIs that are not using the **NETL CO2U openLCA LCI Database**, may use NETL unit process data from the “NETL Unit Process Data” worksheet and GWP impact factors from the “GWP Impact Factors” worksheet.

## 5.6 REPORTING FOR IMPACT ASSESSMENT

The **NETL CO2U LCA Documentation Spreadsheet** is only designed for documenting modeling structure and unit processes when not using openLCA. The life cycle impact assessment and interpretation stages of the analysis shall be reported in the **NETL CO2U LCA Report Template**. See **Section 6.0** for more on reporting requirements for the **NETL CO2U LCA Report Template**. See **Section 2.0** for a more in depth understanding of the reporting requirements in **Section 6.0**.

## 6.0 COMPLETING THE NETL CO2U LCA REPORT TEMPLATE

Documenting the LCA study in a clear and consistent manner is important to effectively communicating the results to DOE and other stakeholders. The LCA report will form part of the Final Scientific/Technical Report for the project. There are various strategies and approaches to documenting LCA results, to ensure consistency across the U.S. DOE Carbon Utilization Program, a standardized report template shall be used by the PIs. The goal is to ensure a minimum level of documentation to effectively communicate the goal of the study, how the study was conducted, and how the results should be interpreted. The focus of this documentation requirement is on content for completeness, in accordance with ISO 14040/14044. **The NETL CO2U LCA Report Template** is provided to assist in the documentation process. PIs shall consider the report template a “guide” and add additional documentation or analysis necessary to effectively communicate the study results.

The following sections describe what to include in each section of the **NETL CO2U LCA Report Template**. The basis for this report is the International Organization for Standardization (ISO) *Environmental Management: Life Cycle Assessment; Requirements and Guidelines*, consistent with **Section 5.2** of ISO 14044. [1] [2] Where applicable, default text that aligns with the U.S. DOE CO2U Use and Reuse Program guidance is recommended within the report template. As defined within this Guidance document, the PIs shall document and report the NETL default modeling product systems – and any alternative product systems recommended by the PIs for consideration with justification for why DOE should also consider these alternatives. The proceeding sections describe the reporting requirements for the NETL default modeling scenario, any additional product systems recommended by the PIs shall follow the same level of documentation recommended.

### 6.1 EXECUTIVE SUMMARY

This section in the **NETL CO2U LCA Report Template** is to 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 and Comparison Product Systems modeled, demonstrate that both systems provide the same service or function to society (both systems have the same functional unit exiting the system boundary), and to assist in the interpretation of results. A brief description of the proposed and Comparison Product Systems shall be provided with a clear definition of the current Technology Readiness Level 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. This section shall state that this LCA is being commissioned for NETL, identify the PIs as the practitioner of the LCA, and that this LCA report has been prepared in accordance with ISO 14040/14044 requirements for public release of comparative assessments for third-parties.

### 6.2 GOAL OF THE STUDY

The purpose of this section is to describe why the study was conducted, how the information/results will be used, by who, and if the study is intended to be made public. These goals are generally the same for all U.S. DOE Carbon Use and Reuse projects. Slight variations based on the TRL of the project exist and shall be clarified in this section of the report. For example, a TRL 1-4 project's primary purpose is technology improvement with DOE (the project funder) as the primary audience. Projects with a TRL of 5 or higher are focused 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. Suggested text for PIs consideration and modification is provided in the report template.

### 6.3 SCOPE OF THE STUDY

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 and Comparison Product Systems. Expectations for sensitivity and uncertainty analysis shall also be described in this section. Variability between U.S. DOE Carbon Use and Reuse projects is expected based on TRL status, project complexity, and expected market effects. At a minimum, the following items shall be defined with respect to the PIs specific project in this section of the report:

1. Functional unit of the study
  - a. 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”
  - b. The primary product of interest is set to 1 unit and the other coproducts are expressed as the appropriate ratio to the primary product of interest
  - c. The Comparison Product System must meet the same function or service provided to society by all of the coproducts produced within the Proposed Product System
2. System boundary
  - a. Describe the life cycle stages included, and if applicable excluded, from the study
  - b. Provide an illustrative depiction of the process flow diagram for both the Proposed and Comparison Product Systems; key material and energy inputs, reference flows, and the functional unit shall be included on the diagram describing the system boundary
3. Carbon dioxide source
  - a. Clearly define the source and CO<sub>2</sub> quality properties as received by the utilization project site
  - b. NETL default scenario options are summarized below
    - i. Flue gas diversion, no additional removal of impurities to concentrate the carbon dioxide stream and no compression or other significant energy expended by the power plant to prepare the flue gas for transport to the utilization project site; NETL default scenario options are summarized below
      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)
    - ii. Captured CO<sub>2</sub>, material and energy are expended to remove impurities to concentrate the CO<sub>2</sub> stream and energy is expended to compress the CO<sub>2</sub> intermediate product to improve transport efficiency; NETL default scenario options are summarized below
      1. Sourced from retrofit power plant; two design options
        - a. Derate - modify the existing plant to operate the carbon capture and compression systems, this results in a reduction of the power plants net power output due to the increased on-site parasitic load
        - b. External auxiliary power/steam facility – a separate energy facility is constructed to provide the electrical and steam requirements to operate the carbon capture and compression systems; no loss of net power to the original power plant
      2. Sourced from a greenfield [new construction] power plant (supercritical pulverized coal power plant); plant is designed to support the energy needs of the carbon capture and compression systems to optimize efficiency
4. Technology representativeness
  - a. Describe the state of the Proposed Product System based on the current research and development performance at the stated TRL
  - b. Describe any performance adjustments required to represent commercial performance expectations for alternative product systems modified to represent commercial/market performance
    - i. 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
    - ii. 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
  - c. Market share is considered part of the technology representativeness, clearly describe any scenarios or sensitivity requirements for evaluating market effects
    - i. 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)
    - ii. 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

- d. Comparison product systems 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
  - i. 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
  - ii. 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
5. Geographical representativeness
  - a. All CO2U projects and their products shall be produced and consumed in the United States of America
  - b. The physical location of CO<sub>2</sub> source and CO2U production facility may or may not be known depending on the state of the project; 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, then U.S. profiles shall be used in alignment with the defined geographical scope
  - c. The geographical representativeness of each primary life cycle stage/supply chain shall be documented; any key deviations shall be noted and explained (e.g., use of foreign profile to describe U.S. operations)
6. Temporal representativeness
  - a. 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 – need to adequately describe why the temporal boundaries (study period) was defined for the LCA study
  - b. 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, what is the service life of each product and how will the carbon 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
  - c. 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
7. Life cycle impact assessment methods for results interpretation
  - a. Required: global warming potential (kg CO<sub>2</sub>e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100
  - b. Optional: global warming potential (kg CO<sub>2</sub>e), based on IPCC AR5, 20-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-20
  - c. Optional: non-greenhouse gas impact assessment methods; NETL recommends the following U.S. EPA TRACI mid-point impact assessment methods for consideration
    - i. Acidification Potential (kg SO<sub>2</sub>e); abbreviation: AP
    - ii. Particulate Matter Formation Potential (kg PM<sub>2.5</sub>e); abbreviation: PMFP
    - iii. Photochemical Smog Formation Potential (kg O<sub>3</sub>e); abbreviation: PSFP
    - iv. Eutrophication Potential (kg Ne); abbreviation: EP
    - v. Ozone Depletion Potential (kg CFC-11e); abbreviation: ODP
  - d. Optional: water consumption (l); abbreviation: WC
  - e. Pls may propose additional impact categories of interest; source and method must be clearly described
8. Completeness requirements
  - a. 99% of the carbon and energy inputs and outputs to the system boundary (carbon and energy balance)
  - b. 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)
9. Sensitivity and uncertainty analysis
  - a. Describe the expectations for how sensitivity and uncertainty will be modeled within the study
  - b. 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)

- c. 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 and Comparison Product Systems modeled
  - d. Describe under what modeling conditions the results of the LCA study would change the outcome of the comparison; a break-even analysis is one technique often used to determine the technical boundaries for environmental preferability
10. Reporting units and method of comparison
- a. NETL standard is International System of Units (SI) reported in scientific notation (e.g., 2.34+01 kg CO<sub>2</sub>e)
  - b. NETL default comparison requirement is three forms/metrics:
    - i. Stacked bar chart with uncertainty bars
    - ii. Ratio of Proposed/Comparison Product System
    - iii. Percent change calculation of the Proposed Product System from the Comparison Product System

## 6.4 LIFE CYCLE INVENTORY ANALYSIS

The purpose of this section is to document “how” the life cycle of the Proposed and Comparison Product Systems 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 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. At a minimum, the following items shall be defined with respect to the PIs specific project in this section of the report:

1. Modeling platform
  - a. The following three options are presented in this guidance document for modeling; specify the selected method and if the underlying model will be provided as part of the Final Scientific/Technical Report
    - i. openLCA
      1. Modified **NETL CO<sub>2</sub>U openLCA LCI Database** with project LCA and sensitivity/uncertainty analysis
      2. Completed **NETL CO<sub>2</sub>U openLCA Results Contribution Tool**
      3. Completed **NETL CO<sub>2</sub>U LCA Report Template**
    - ii. PI spreadsheet model
      1. Completed **NETL CO<sub>2</sub>U LCA Documentation Spreadsheet** and supporting materials used outside of the software (e.g., results interpretation spreadsheets)
      2. Completed **NETL CO<sub>2</sub>U LCA Report Template**
    - iii. Third-party LCA software
      1. Submit LCA data via one of the two methods:
        - a. Provide final LCA model database file and supporting materials used outside of the software (e.g., results interpretation spreadsheets) with NETL
        - b. If PIs do not want to provide the LCA model database, submit completed **NETL CO<sub>2</sub>U LCA Documentation Spreadsheet** and supporting materials used outside of the software (e.g., results interpretation spreadsheets)
  - b. The model shall be provided to NETL to facility the third-party review
  - c. If the PIs choose to provide the model as part of the Final Scientific/Technical Report, the model can provide the documentation for unit processes and data sources modeled; significantly reducing (but not eliminating) the level of documentation required in the written **NETL CO<sub>2</sub>U LCA Report Template**
2. Unit process descriptions
  - a. 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)
  - b. A unit process “map” or “organizational hierarchy” that aligns to the system diagram is helpful to ensure transparency of how the model was assembled (optional)
3. Data sources and quality assessment

- a. Document the source of each piece of data used in the analysis
  - b. Describe the sources of data
    - i. PI-provided data – describe how the data was collected and why it is representative of the process of interest
    - ii. Third-party data – describe the source and why it is representative of the process of interest
  - c. 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
    - i. 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
  - d. Ensure the above is completed for the “Low”, “Expected”, and “High” modeling scenarios
4. Results of inventory completeness check
    - a. 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 than only a reference to the model is required for documentation
    - b. Describe any exclusions of unit processes or supporting supply chains resulting from the use of cut-off criteria for each product system
  5. Results of life cycle inventory model sensitivity check
    - a. Document the relative sensitivity of key model parameters on the LCI results; a tornado diagram is a common method for reporting sensitivity results
    - b. Model parameters with significant sensitivity shall be included in the results interpretation to determine the effect on the final study results
  6. Allocation procedures (optional)
    - a. NETL default is system expansion to avoid allocation at the system level
    - b. Allocation within a unit process shall be described within each unit process description
    - c. If 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

## 6.5 LIFE CYCLE IMPACT ASSESSMENT

The purpose of this section is to document the impact assessment methods defined in the Scope of the Study section to be included in the analysis. The NETL minimum requirement is life cycle greenhouse gas 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 options 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.

At a minimum, the following items shall be defined with respect to the PIs specific project in this section of the report:

1. Life cycle impact assessment methods
  - a. Describe each life cycle impact assessment method applied in the LCA
  - b. It is expected that PIs will utilize a pre-existing life cycle impact assessment methods, if not, full documentation and justification of custom impact assessment methods shall be included in the report
2. Data quality assessment
  - a. Describe any known data limitations, omissions of inventory data, that may affect the interpretation of each impact categories result

- b. 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
  - i. Expectation for “document the findings” – the results of the environmental relevance check can be documented within the openLCA model or a side analysis in a secondary software application (e.g., Microsoft Excel™)
  - ii. A statement in the report describing 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
3. Life cycle impact assessment results
  - a. 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
  - b. Recommend providing detailed results by product system in an Appendix and comparing the proposed and Comparison Product System results for key life cycle stages in the Life Cycle Interpretation section of the report

Text describing each of the NETL recommended impact assessment methods is provided in the report template. The PIs shall modify the text as appropriate to reflect the scope of the impact assessment methods used in the study.

## 6.6 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. Life cycle interpretation phase of an LCA is an iterative process of assessing the data quality, refining the life cycle inventory modeling as necessary, and determining if sufficient data exists to produce and compare impact assessment results for each impact category proposed in the Scope of the Study. At a minimum, the comparative LCA must be capable of comparing the greenhouse gas emissions to meet the primary Goal of the LCA.

Results reporting and interpretation have been streamlined for PIs that choose to use the openLCA modeling framework. The **NETL CO2U openLCA Results Contribution Tool** was designed to help evaluate, interpret, and report LCA study results by impact category. At a minimum, the following items shall be defined with respect to the PIs specific project in this section of the report:

1. Compare the Proposed Product System to the Comparison Product System and calculate the following result interpretations for global warming potential (kg CO<sub>2</sub>e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100 (required)
  - a. Stacked bar chart with uncertainty bars
  - b. Ratio of Proposed/Comparison Product System
  - c. 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 and Comparison Product Systems; 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

## 6.7 CRITICAL REVIEW

U.S. DOE’s Carbon Utilization Program will serve the role of critical review for this process. Recommended text is suggested in the report template. If additional critical reviews are conducted prior to submission DOE, the names, affiliations, and contact information shall be documented for each external reviewer.

## 6.8 REFERENCES

This section is for a list of references used in the report.

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# APPENDIX A: ACCESSING THE NETL CO2U LCA TOOLKIT AND RESOURCES FOR ASSISTANCE

The **NETL CO2U LCA Guidance Toolkit** is designed to provide requirements and assistance to PIs as they complete an LCA of their project as required by the U.S. DOE Carbon Utilization Program. The **NETL CO2U LCA Guidance Toolkit** includes the following:

1. **NETL CO2U LCA Guidance Document** (this document) outlines the analysis requirements and how to use the supporting data and tool
2. **NETL CO2U openLCA LCI Database** is an openLCA database that includes NETL unit process data and an example CO2U LCA
3. **NETL CO2U openLCA Results Contribution Tool** is a Microsoft Excel™ template that translates openLCA results into required charts
4. **NETL CO2U LCA Documentation Spreadsheet** is a Microsoft Excel™ file that can be used to document data when not using openLCA
5. **NETL CO2U LCA Report Template** is a Microsoft Word™ report template for summarizing data and results
6. **NETL CO2U openLCA Model Training Resources** will be provided to PIs to aid in the implementation of their LCA in the openLCA modeling platform
7. **NETL CO2U LCA Subject Matter Expert Support** will be available to PIs as they work through all phases of the LCA from conception to documentation\*

\*PIs may reach out to **NETL CO2U LCA Subject Matter Expert** for input by sending an email to [LCA@netl.doe.gov](mailto:LCA@netl.doe.gov)

The entire contents of the **NETL CO2U LCA Toolkit** can be accessed at the following URL:

<http://netl.doe.gov/LCA/CO2U>

The openLCA software can be downloaded at the following URL:

<http://www.openlca.org/form/>

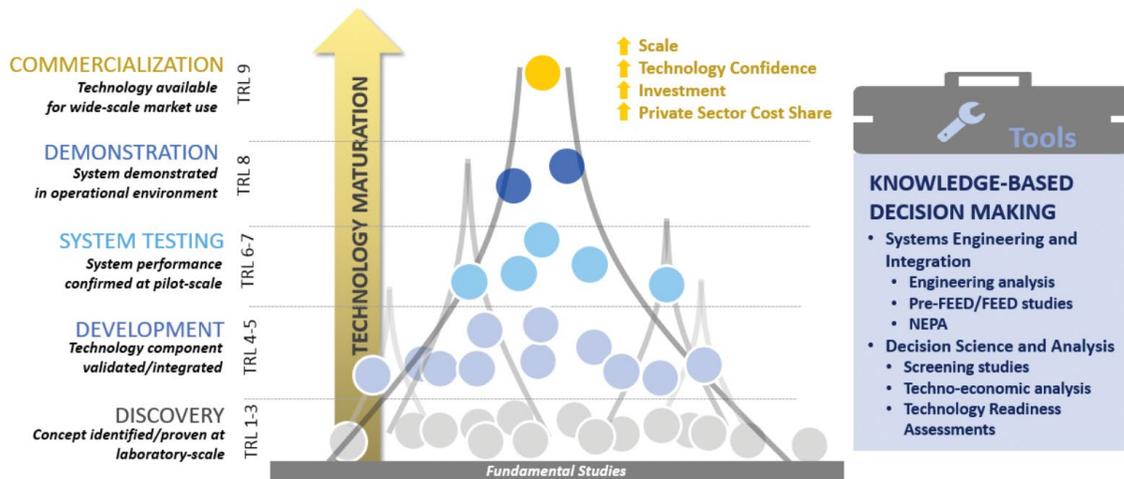
# APPENDIX B: U.S. DOE TECHNOLOGY READINESS LEVELS

The Technology Readiness Assessment (TRA) process is defined as a “systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.” TRA serves to methodically assess the state of the technology development spanning progress from early research on basic principles through large-scale testing and evaluation prior to commercial deployment. Technology development typically advances over a multi-year period and designs are incrementally refined until a suitably sized, successful demonstration is completed. TRA is particularly useful in establishing a consistent set of terminologies and a rigorous evaluation process that can be used to clearly establish a technology’s current state of progress.

The Technology Readiness Level (TRL) for a technology is established based upon the scale, degree of system integration, and test environment in which the technology has been successfully demonstrated. **Exhibit B-1** provides a schematic outlining the progression of the nine TRLs from concept to market readiness. **Exhibit B-2** includes a summary of characteristics at different development scales.

By more clearly understanding the current state and assessing the degree of development that yet remains, TRA emerges as a useful tool in the planning of future Research and Development (R&D) activities. The U.S. Department of Energy (DOE) TRA Guide<sup>a</sup> provided the foundation for the assessment of R&D projects conducted by the National Energy Technology Laboratory (NETL). Accordingly, TRL definitions and descriptions were tailored to the R&D being conducted at NETL (Refer to **Exhibit B-3** for Office of Fossil Energy and NETL TRL definitions and descriptions). Although the definitions imply a linear progression in technology advancement, the use of advanced simulation may support accelerated and lower-risk R&D and commercialization.

**EXHIBIT B-1. TECHNOLOGY READINESS LEVEL—RELATIONSHIP TO MARKET READINESS AND DEGREE OF INTEGRATION**



<sup>a</sup> United States Department of Energy, Office of Fossil Energy. DOE-FE Technology Readiness Assessment Guide—DRAFT. September 2011, <http://www2.lbl.gov/DIR/assets/docs/TRL%20guide.pdf>

EXHIBIT B-2. SUMMARY OF CHARACTERISTICS AT DIFFERENT DEVELOPMENT SCALES

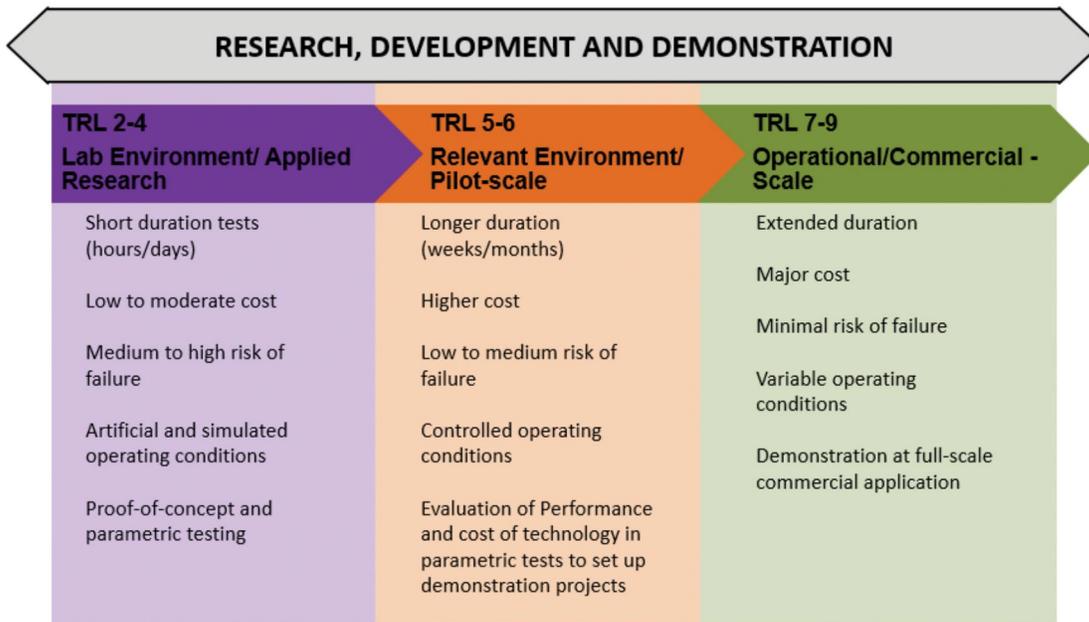


EXHIBIT B-3. TECHNOLOGY READINESS LEVEL DEFINITIONS, DESCRIPTIONS, AND SYSTEMS ANALYSIS BEST PRACTICES

TRL	DEFINITION	DESCRIPTION	SYSTEM ANALYSIS BEST PRACTICES
1	Basic principles observed and reported.	<b>Core Technology Identified.</b> Scientific research and/or principles exist and have been assessed. Translation into a new idea, concept, and/or application has begun.	<b>Assessment:</b> Perform an assessment of the core technology resulting in (qualitative) projected benefits of the technology, a summary of necessary R&D needed to develop it into the actual technology, and principles that support the viability of the technology to achieve the projected benefits.
2	Technology concept and/or application formulated.	<b>Invention Initiated.</b> Analysis has been conducted on the core technology for practical use. Detailed analysis to support the assumptions has been initiated. Initial performance attributes have been established.	<b>White Paper:</b> A white paper describing the intended commercial application, the anticipated environment the actual technology will operate in, and the results from the initiation of a detailed analysis (that will at least qualitatively justify expenditure of resources versus the expected benefits and identify initial performance attributes).
3	Analytical and experimental critical function and/or characteristic proof-of-concept validated.	<b>Proof-of-Concept Validated.</b> Performance requirements that can be tested in the laboratory environment have been analytically and physically validated. The core technology should not fundamentally change beyond this point. Performance attributes have been updated and initial performance requirements have been established.	<b>Performance Model and Initial Cost Assessment:</b> A basic model of the technology concept, incorporating process boundary conditions, that provides insight into critical performance attributes and serves to establish initial performance requirements. These may be empirically or theoretically based models represented in Excel or other suitable platforms. In addition, an initial assessment and determination of performance requirements related to cost is completed.

TRL	DEFINITION	DESCRIPTION	SYSTEM ANALYSIS BEST PRACTICES
4	Basic technology components integrated and validated in a laboratory environment.	<b>Technology Validated in a Laboratory Environment.</b> The basic technology components have been integrated to the extent practical (a relatively low-fidelity integration) to establish that key pieces will work together, and validated in a laboratory environment. Performance attributes and requirements have been updated.	<b>System Simulation and Economic Analysis:</b> These models incorporate a performance model of the technology in its target application, and will compare ideal attribute requirements against data gathered through R&D tests. These models should be comparable in detail to those found in the Baseline Series published by NETL <sup>b</sup> and follow the QGESS documents also published by NETL. Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment. In addition, an economic analysis of the technology is completed, assessing the impact of capital costs, operating and maintenance costs, and life on the impact of the technology and its contributions to the benefits of the overall system in a commercial environment.
5	Basic technology components integrated and validated in a relevant environment.	<b>Technology Validated in a Relevant Environment.</b> Basic technology component configurations have been validated in a relevant environment. Component integration is similar to the final application in many respects. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	<b>System Simulation and Economic Analysis Refinement:</b> A more detailed process model for the technology, compared against empirical data gathered in the laboratory, will be developed and incorporated into system simulations. This provides greater fidelity in the performance and cost estimation for the technology, facilitating updates to performance attributes and requirements (including updates to the economic analysis). This also allows greater evaluation of other process synergy claims (e.g., state-of-the-art technology is improved by the use of the new technology). Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment.
6	Prototype validated in a relevant environment.	<b>Prototype Validated in Relevant Environment.</b> A prototype has been validated in a relevant environment. Component integration is similar to the final application in most respects and input and output parameters resemble the target commercial application to the extent practical. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	<b>System Simulation and Economic Analysis Refinement:</b> Performance and cost models are refined based upon relevant environment laboratory results, leading to updated performance attributes and requirements. Preliminary steady-state and dynamic operations analysis (as appropriate for the technology) completed on all critical process parameters (i.e., upper and lower operating limits). Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment. Key process equipment should be specified to the extent that allows for bottoms-up estimating to support a feasibility study of the integrated system.
7	System prototype validated in an operational system.	<b>System Prototype Validated in Operational Environment.</b> A high-fidelity prototype, which addresses all scaling issues practical at pre-demonstration scale, has been built and tested in an operational environment. All necessary development work has been completed to support Actual Technology testing. Performance attributes and requirements have been updated.	<b>System Simulation and Economic Analysis Refinement:</b> Performance and cost models are refined based upon relevant environment and system prototype R&D results. The refined process, system, and cost models are used to project updated system performance and cost to determine if the technology has the potential to meet the project goals. Performance attributes and requirements are updated as necessary.
8	Actual technology successfully commissioned in an operational system.	<b>Actual Technology Commissioned.</b> The actual technology has been successfully commissioned for its target commercial application, at full commercial scale. In almost all cases, this TRL represents the end of true system development.	<b>System Simulation and Economic Analysis Validation:</b> The technology/system process models are validated by operational data from the demonstration. Economic models are updated accordingly.
9	Actual technology operated over the full range of expected operational conditions.	<b>Commercially Operated.</b> The actual technology has been successfully operated long-term and has been demonstrated in an operational system, including (as applicable) shutdowns, startups, system upsets, weather ranges, and turndown conditions. Technology risk has been reduced so that it is similar to the risk of a commercial technology if used in another identical plant.	<b>Commercial Use:</b> Models are used for commercial scaling parameters.

<sup>b</sup> Performing a Techno-Economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015.

# APPENDIX C: ALTERNATIVE CO-PRODUCT MANAGEMENT METHODS

Principal investigators (PIs) shall use system expansion in their life cycle analysis (LCA) that yields a multiproduct functional unit, but if PIs would like to generate a separate set of results with a single functional unit, they may use displacement or allocation as described below.

With the displacement *co-product management* method, the system boundary is first expanded to include each co-product. The LCA model results are generated for both the Proposed Product System and Comparison Product System, as they would occur in system expansion. The multiproduct functional unit is then reduced to a single-product functional unit by looking at the products that one wants to remove from the system and subtracting the impact of the products in the comparison process from the carbon dioxide utilization (CO2U) process that are being replaced (this is also referred to as displacement, where one implicitly assumes that the existing product in the market will be substituted in the market with the product from the CO2U process—a market analysis is often used to determine the level of substitution and if consumption of the product will increase or decrease as a result of the introduction of the new proposed product to the market; for projects with a low Technology Readiness Level (TRL) (<4), a one-for-one (100%) market substitution is a reasonable modeling assumption if a market analysis has not been conducted and no other known or anticipated market effects are reasonable foreseen by the PIs). A market analysis shall be conducted for any project transitioning into TRL 4 or higher at the time of delivery of the CO2U LCA—the market analysis data shall be used to inform the long-run marginal *producer* for each product in the comparison process. This knowledge shall be used to inform the displacement choice for each co-product. If a market analysis has not been conducted and market effects are reasonable foreseen, then a sensitivity analysis shall be performed and reported with the final results to assess the impact of this modeling choice on the interpretation of results. The goal of the sensitivity analysis in this situation is to determine at what level (percent) of market substitution the CO2U process would be preferred over the comparison process. Application of system expansion with displacement is done one-by-one for each product until only the desired product is left visible in the system. This single co-product CO2U process is then compared with the equivalent comparison process providing the same function or service to society.

With the allocation co-product management method, each unit process with multiple co-products is adjusted so that there is only one product *before* the model is run. In allocation, the inputs and outputs of the process are split into their portion of contribution, so that, for example, an output of 75 kilograms (kg) of product A and 25 kg of product B is 75 percent product A and 25 percent product B. If PIs want to only include product A, one would reduce the inputs and outputs by 25 percent, if in this example, a physical relationship based on mass is determined reasonable to allocate (or assign) the life cycle burdens based on the mass ratio of the final products.<sup>a</sup> Unfortunately, it is usually the case that the co-products provide vastly different services to society and a physical relationship between the products cannot be established. When products differ in common reporting units of mass, volume, energy, or economics, this is a good indicator that a physical relationship cannot be reasonably established. There are even instances where similar units are used between co-products, but a single physical allocation method is not ideal, these systems (such as CO<sub>2</sub> captured at a power plant coupled with enhanced oil recovery [EOR]) produce two disparate energy products (electricity and crude oil) that provide very different services to society.

When considering a physical allocation method, one must consider the role of the unit process in the life cycle for which the allocation is being considered. If the unit process invests the same materials and energy inputs to the unit process to provide the service independent of the ratio of the co-products produced or managed by the unit process, then physical allocation may be reasonable. For example, for a single truck that transports two products from point A to B, the materials and energy inputs are based on the volume (in general) of the products being transported by the truck; therefore, each product should be assigned responsibility for the share of the environmental outputs based on their ratio of the volume of each transported. Another example is a natural gas liquids separator that removes heavier hydrocarbons (e.g., natural gas liquids) from lower hydrocarbons (e.g., methane) entering the separation unit. In this example, the purpose of the separator is to split the input product stream into two separate product streams based on the molecular weight of the products.<sup>b</sup> Therefore, the physical allocation method is based on mass but the units of these products are often reported in terms of volume or energy content. After the appropriate physical allocation methods are applied and documented with a justification for the selection of the allocation method, the mass quantities can be converted to their common reporting units to improve communication and interpretation of the model and results. Unit conversion factors shall be documented in the model and report.

Economic allocation is another method identified by International Organization for Standardization (ISO) to assign environmental

- <sup>a</sup> This is an expanded way of presenting the allocation calculation and is helpful from an instructive perspective. However, when using mass allocation, the scaling of unit process flows down to the mass share of a single product followed by the scaling of the unit process up to one mass unit of exactly one product are inverse operations. If all co-products are on a mass basis, a simpler way to account for mass allocation is to normalize the unit process to a total output of 1 kg of total product (assuming that the original reference flow of the unit process was 1 kg of a single product).
- <sup>b</sup> Some oil/gas or oil/gas/liquid separators are passive and do not require energy input, thus making allocation trivial. In instances where a heater may be employed by a separator, input energy must be allocated across co-products.

outputs to multiple products. Economic allocation requires knowledge of the cost to produce each product, absent any company profit or adjustments for consumer demand (willingness-to-pay). It is critical to ensure that any economic values utilize the production cost and not the consumer/market price of the product. Price of a product includes the effects of supply and demand and company profit. These additions to the production cost value implicitly apply a value-based judgement of the market's willingness-to-pay for one product in comparison to another. Therefore, "consumer/market price" does not reflect solely the material and energy inputs to the system. Depending on the market for the product, the difference between the ratio of the production cost and consumer/market price may be very similar. In some markets, company profit ratios are fairly equivalent between providers and market may be inelastic to changes in supply and demand. In these cases, a justification supporting the above assertions can be documented to allow the use of consumer/market price as the ratio between the production cost and consumer/market price can be considered equivalent. In general, consumer/market prices are much more commonly available in public data than production cost data—often a limitation to using economic allocation is availability of production cost data for all co-products.

When selecting the co-product management option, it is important to recognize the difference between system expansion with displacement and physical or economic allocation. System expansion with displacement accounts for market consequences—either directly or indirectly. Physical and economic allocation do not account for market consequences. Economic allocation methods should not be confused with the use of economic data to determine the marginal-producer within a market that would be displaced by the proposed product. System expansion with or without displacement accounts for market consequences, directly or indirectly, by using the long-run marginal price from general equilibrium models that have a fixed demand for each product. In this situation, the use of consumer/market price values are preferred to production cost values to account for society's willingness-to-pay for one product type over another.

System expansion with displacement is preferred over allocation when the goal of the LCA is to perform a comparison to inform a decision. In these cases, it is preferred to account for the external market consequences of selecting one system/product over another. LCAs performed for the purposes of identifying improvement opportunities within the CO2U process, non-comparative, generally prefer physical or economic allocation to remove external market consequences from the system boundary because they are factors outside a product owners' control—ability to directly improve the environmental performance. Secondly, system expansion with displacement is often preferred because of the difficulty in determining a physical relationship between the co-products or the actual production cost of each product. When no reasonable allocation method can be determined, a range of allocation methods should be applied to bracket the modeling uncertainty introduced into the LCA model and its effect on results interpretation.

It should be noted that there may be some processes where each unit of the input to the process can be attributed precisely to each unit of the output, and partitioned or assigned to each product. Intimate knowledge of the engineering details of the process are needed. For example, the engineer that designed the process may know that 70 percent of the natural gas input is used for product A and 30 percent for product B, but 60 percent of the electricity input is used for product B and 40 percent for product A. Similarly, the engineer can link the percent of each emission to the inputs as well. In that case, allocation factors are not necessary to reduce the functional unit. This is often referred to as "avoiding allocation by partitioning."

There may be cases where it is acceptable to combine system expansion with displacement and allocation within the same LCA system boundary. For example, many unit processes used in LCA are black box unit processes that have already had allocation applied to them to create a single-product unit process. This is not uncommon in pre-packaged life cycle inventory (LCI) data sets designed to provide cradle-to-gate environmental data for material and energy inputs to unit process within the LCA system boundary. When these unit processes are used in LCAs that use system expansion with displacement, one would technically end up with a system that includes both allocation and system expansion with displacement.

# APPENDIX D: ELECTRICITY MIX DATA DEVELOPMENT

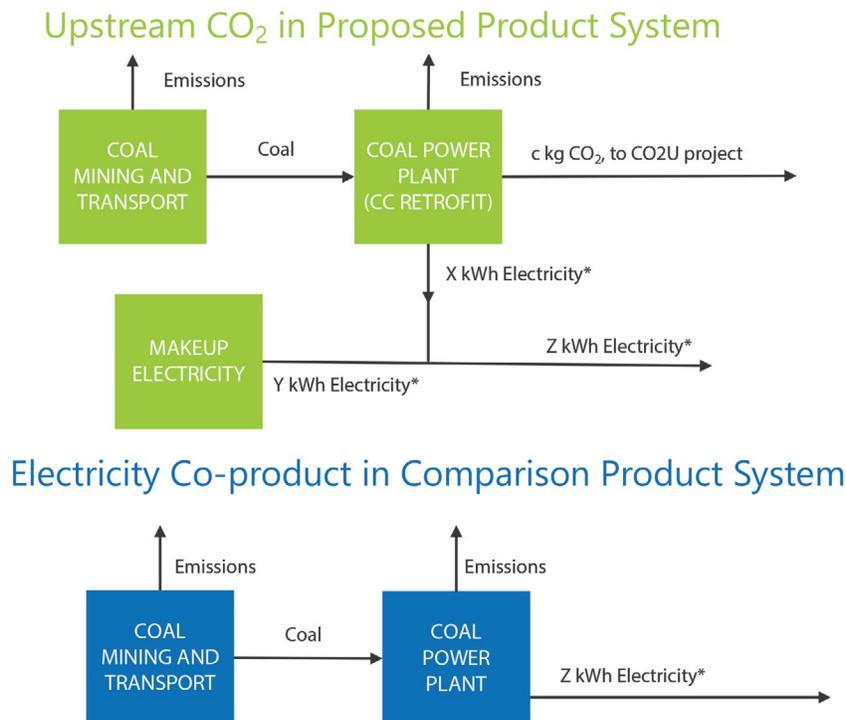
As described in **Section 2.1.5**, the upstream carbon dioxide (CO<sub>2</sub>) source choice affects the analysis results. CO<sub>2</sub> can be sourced from flue gas or captured CO<sub>2</sub>, from new or existing plants, and from power or industrial sources. This influences the goal and scope of the study that guides the Comparison Product System and other study design choices strongly. Based on the modeling framework established within these guidelines, all U.S. Department of Energy Carbon Use and Reuse carbon dioxide utilization (CO<sub>2</sub>U) projects will have a minimum of two products exiting the system boundary. This is because the source of the CO<sub>2</sub> material input into the CO<sub>2</sub>U project (i.e., coal-fired power plant)<sup>a</sup> is included within the system boundary and that source co-produces electricity and CO<sub>2</sub> as products (technosphere flows). Therefore, Principal Investigators (PIs) shall model the Proposed Product System with the CO<sub>2</sub> source coming from a coal-fired power plant with an electricity co-product (see blue highlighted section of **Exhibit 2-5**).

This Appendix provides details on the calculation of the electricity flows in the Proposed and Comparison Product Systems to ensure functional equivalency, as well as, background and assumptions on the technology mixes that are be used to represent those electricity flows.

## D.1 COMPARISON PRODUCT SYSTEM DEFINITION FOR CO<sub>2</sub> SOURCED FROM A RETROFIT (DERATE) POWER PLANT EQUIPPED WITH CARBON CAPTURE TECHNOLOGY

The National Energy Technology Laboratory default parameters CO<sub>2</sub> sourced from a retrofitted (derated) power plant equipped with carbon capture technology shall be a subcritical pulverized coal (SubPC) power plant producing captured CO<sub>2</sub> and electricity co-products. The amount of makeup electricity in the Proposed Product System shall be equal to the derate from adding the carbon capture and compression equipment to the plant (i.e., retrofit), m percent of the electricity co-product in the Proposed Product System (X in **Exhibit D-1** [identical to **Exhibit 2-14**]). The calculated amount of makeup electricity in the Proposed Product System (Y in **Exhibit D-1** [identical to **Exhibit 2-14**]) is defined by the following equation:

**EXHIBIT D-1. ELECTRICITY SUB-SYSTEM FOR CAPTURED CO<sub>2</sub> FROM RETROFIT WITH DERATE**



\*The carbon capture plant loses some of its capacity to run the carbon capture equipment, so makeup electricity in the Proposed Product System is required to have the same amount

<sup>a</sup> This guidance is specific to the use of CO<sub>2</sub> obtained from a coal-fired power plant. The methodology and application can be applied to other sources of anthropogenic CO<sub>2</sub> obtained for use as a material input to a CO<sub>2</sub>U project.

of electricity output. The amount of makeup electricity is defined based on the capacity of the derate (MW) and the assumed operating capacity factor of the plant.

$$Y = m * X$$

**EQUATION D-1**

Where:

Y = the calculated amount of makeup electricity in the Proposed Product System

X = the amount of electricity co-product coming from the CO<sub>2</sub> source (i.e., the power plant)

m = the percent of the net capacity of the CO<sub>2</sub> source which is spent on CO<sub>2</sub> capture auxiliaries, inherent in the power plant profile being used

Additionally, the value of X may not be readily available. Some life cycle assessment software will allow you to preview the outputs of processes before calculations, in which case the user can check that and manually input the value of X as the value of the electricity output from the makeup electricity. However, other software such as openLCA will not permit that. Either way, the way to automatically calculate the value of X will be to multiply the amount of CO<sub>2</sub> the CO2U process requires (c in **Exhibit D-1**) by the ratio of CO<sub>2</sub> to electricity co-product coming from the power plant (n in **Exhibit D-2**)

$$X = n * c$$

**EQUATION D-2**

Where:

n = the electricity co-product to captured carbon dioxide ratio, inherent in the power plant profile being used

c = the carbon dioxide required by the CO2U project

To ensure the Comparison Product System includes the exact total electricity crossing the boundaries of the Proposed Product System, the electricity coming from the power plant in the Comparison Product System is set to Y. Z is determined by adding Y to X:

$$Z = X + Y$$

**EQUATION D-3**

Where

Z = is the calculated amount of electricity co-product and make-up electricity in the Proposed Product System and is the total amount of electricity co-product in the Comparison Product System.

By combining **Equation D-1**, **Equation D-2**, and **Equation D-3**, we find that:

$$Y = m * n * c$$

$$Z = n * c * (1 + m)$$

In which m and n are provided by NETL for any NETL-based power plant profiles and c is determined by the Pls' CO2U process.

The values of m and n for each type of derated power plant are provided in **Exhibit D-2**.

**EXHIBIT D-2. MODELING CONSTANTS REQUIRED TO CALCULATE MAKEUP ELECTRICITY REQUIRED FOR CO<sub>2</sub> SOURCED FROM A DERATED RETROFIT**

POWER PLANT TYPE	CASE NAME IN REF	M [kWh/kWh]	N [MJ/kg]
SCPC	B12B	0.09665	4.12272
SubPC*	B11B	0.09665	3.95517

*\*SubPC power plants are considered the default for retrofitted carbon capture scenarios*

The m values were calculated using the net capacities and CO<sub>2</sub> auxiliary loads from the NETL Cost and Performance Baseline for

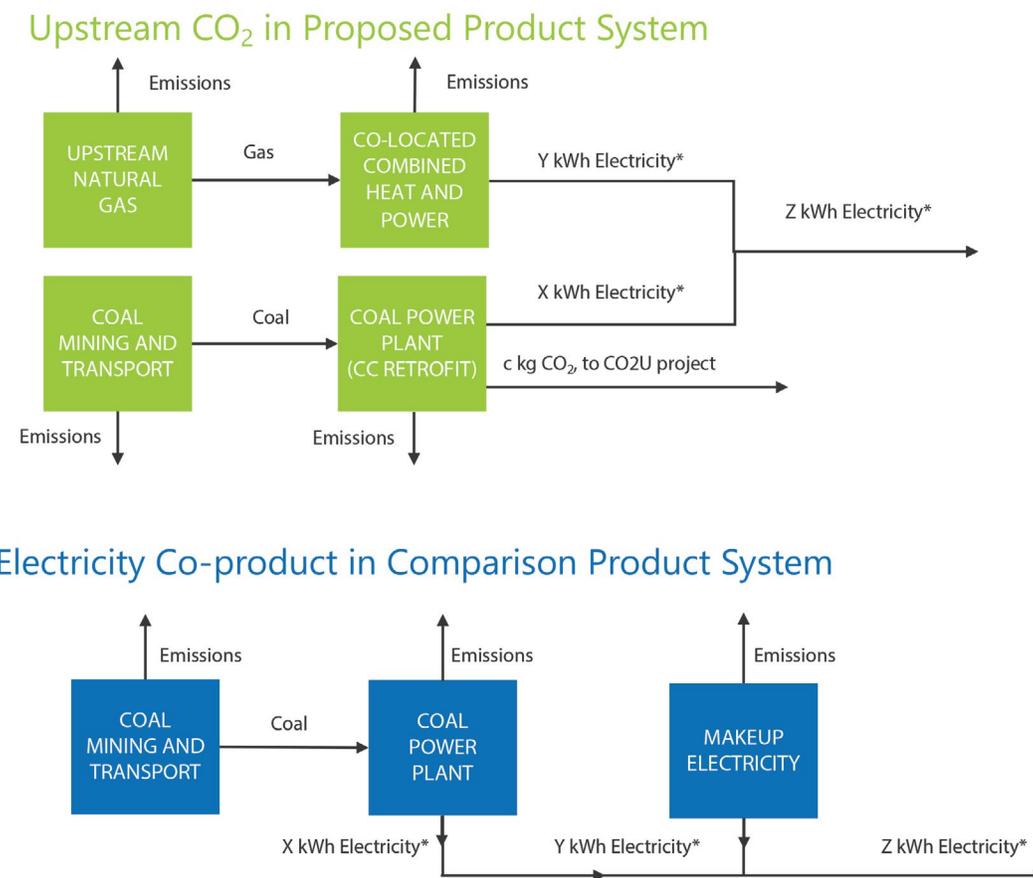
Fossil Energy Plants, Volume 1a [20]. The  $n$  values were calculated based on the net electricity and captured carbon dioxide outputs from that same study [20]. The subPC and supercritical pulverized coal (SCPC) power plants in that study are modeled as 550 megawatt (MW) net capacity plants with carbon capture systems catching 90% of the CO<sub>2</sub>. The natural gas combined cycle plant is modeled as a 559 MW net capacity plants with carbon capture systems catching 90% of the CO<sub>2</sub>.

If the Pls use the openLCA database provided by NETL, this math will occur automatically as long as the Pls use the “CO<sub>2</sub> Source Mixer – Prop” unit process provided in the NETL Unit Process Library as the default provider for the carbon dioxide or flue gas input to their CO2U process. Then, the Pls can use the “CO<sub>2</sub> Source Mixer – Comp” process as an input to their comparison process and input the amount of CO<sub>2</sub> or flue gas being used in the Proposed Product System. This is further discussed in **Section 3.0**.

## D.2 COMPARISON PRODUCT SYSTEM DEFINITION FOR CO<sub>2</sub> SOURCED FROM A RETROFIT POWER PLANT (ON-SITE CO-LOCATED COMBINED HEAT AND POWER) EQUIPPED WITH CARBON CAPTURE TECHNOLOGY

The default CO<sub>2</sub> shall be a SubPC power plant producing captured CO<sub>2</sub> and electricity co-product ( $X$ ) with a natural gas power plant (modeled as a simple cycle gas turbine [GTSC]) producing auxiliary power ( $Y$ ). The SubPC/GTSC plants function together as one unit, producing the total electricity, ( $Z$ ). The amount of makeup electricity ( $X$ ) in the Comparison Product System shall be  $m$  percent of the total electricity co-product in the Proposed Product System ( $Z$  in **Exhibit D-3** [identical to **Exhibit 2-16**]):

**EXHIBIT D-3. ELECTRICITY SUB-SYSTEM FOR CAPTURED CO<sub>2</sub> FROM RETROFIT WITH ON-SITE CO-LOCATED COMBINED HEAT AND POWER (NO DERATE)**



\*The carbon capture plant gains capacity by installing auxiliary power to run the carbon capture equipment, so makeup electricity in the Comparison Product System is required to have the same amount of electricity output. The amount of makeup electricity is defined based on the capacity of the auxiliary combined heat and power unit (MW) and the assumed operating capacity factor of the plant.

$$Y = m * Z$$

EQUATION D-4

Where:

$Y$  = the calculated amount of makeup electricity in the Comparison Product System

$Z$  = the total amount of electricity coming from the captured power plant in the Proposed Product System

$m$  = the percent of the net capacity of the CO<sub>2</sub> source which is provided by the on-site co-located combined heat and power (CHP) plant (the natural gas plant).

As was the case with the variable  $X$  in the derate case, the value of  $Z$  may not be readily available and can be found using:

$$Z = n * c$$

EQUATION D-5

Where:

$n$  = the electricity co-product to captured carbon dioxide ratio, inherent in the power plant profile being used

$c$  = the carbon dioxide required by the CO2U project

Additionally, because  $m$  is a percent of  $Z$  in this section,  $X$  can be found through subtraction as in:

$$X = Z - Y$$

EQUATION D-6

Where:

$X$  = the amount of electricity coming from the uncaptured power plant in the Comparison Product System

Altogether, **Equation D-4**, **Equation D-5**, and **Equation D-6** simplify to the following set of equations:

$$Y = m * n * c$$

$$X = n * c * (1 + m)$$

In which  $m$  and  $n$  are provided by NETL for any NETL-based power plant profiles and  $c$  is determined by the Pls' CO2U process.

There is only one NETL-provided power plant profile for this scenario, which is modeled after the power plant provided modeled in the NETL study, "Eliminating the Derate of Carbon Capture Retrofits" [23]. For this scenario,  $m = .2466$  and was found by dividing the capacity of the uncaptured SubPC plant by the capacity of the captured plant with GTSC auxiliary power. Also for this scenario,  $n = 6.577$  and was found by dividing the net output in megajoule (MJ) by the total carbon dioxide captured.

Pls who use the **NETL CO2U openLCA LCI Database** can simply attach the "CO<sub>2</sub> Source Mixer – Prop" and "CO<sub>2</sub> Source Mixer – Comp" unit processes to their systems. Then, these calculations will happen automatically as long as the Pls follow the guidance in **Section 3.0**.

## D.3 DEVELOPMENT OF REGIONAL MARGINAL CAPACITY ADDITION GENERATION TECHNOLOGY MIXES

The global warming potential (GWP) data in **Exhibit 2-13** were developed using a combination of Energy Information Administration (EIA) data to determine the technology mix and NETL life cycle data to determine the associated greenhouse gas (GHG) life cycle inventory (LCI). Data for projected electricity generation capacity additions were developed using the reference case from the 2019 Annual Energy Outlook (AEO), specifically from *Net Summer Electricity Generating Capacity – Cumulative Planned and Unplanned Additions* results sheet. [6, 24, 25] North American Electric Reliability Corporation (NERC) region data was obtained from the regional sheets. Not all of the generation technologies presented in the AEO are available in the NETL Grid Mix Explorer, therefore some technology mapping was performed to provide an approximation of the GHG LCI (see **Exhibit D-4**). The assumptions made

while mapping the technologies (stated below) are justified on the basis that they would not materially change the total GWP estimates for different regional grid mixes.

- “Fuel Cells”, “Municipal Waste”, and “Wood and Other Biomass” were mapped to “Other Renewables” because their individual contributions to the total capacity were de minimis. In the U.S. mix, the maximum capacity addition from fuel cell, municipal waste, and wood and other biomass was 0.03%, 0.01%, and 0.34% of the total addition respectively. In the regional profiles the maximum capacity addition for these technologies were 0.23%, 0.07%, and 2.5% of the total addition respectively.
- In the U.S. mix and most of the NERC regions, wind is the biggest renewable source in terms of contribution to the capacity addition, maximum for U.S. mix and the NERC regions being 27% and 94% respectively. Whereas, the “Other Renewables” category had a maximum contribution of 0.4% and 2.5% in the U.S. mix and the NERC regions respectively. In the absence of specific technologies in the NETL Grid Mix Explorer “Other Renewables” were mapped to “Onshore Wind” as a proxy.
- Both “Solar PV” and “Solar Thermal” are mapped to “Solar Thermal” in the grid mix explorer. This was done because of two reasons, the NETL Grid Mix Explorer consists of only “Solar Thermal” as a solar technology and the life cycle GHG impacts of solar PV and solar thermal are not substantially different relative to higher carbon technologies (46 and 36 g CO<sub>2</sub>e/kWh respectively). [32] Thus, the overall calculated life cycle GHG emissions impact for a regional grid mix would remain nearly the same whether or not the two technologies are combined.

The EIA AEO technology mix includes both offshore wind and wind (assumed to be onshore, since offshore is already segregated). Wind contributes up to 27% to the total capacity addition in the U.S. mix and up to 94% in the NERC regions and offshore wind contribute only up to 0.03% and 0.21% to the total capacity addition in the U.S. mix and the NERC regions, respectively. Therefore, all wind technologies, offshore and onshore, are mapped to onshore wind technology in the NETL Grid Mix Explorer.

The resulting technology breakdown for capacity expansion is provided in **Exhibit D-5**.

#### EXHIBIT D-4. EIA TECHNOLOGY MAPPING - MARGINAL CAPACITY ADDITION GENERATION TECHNOLOGY

EIA AEO TECHNOLOGY	NETL GRID MIX EXPLORER TECHNOLOGY
Coal	Fleet Coal
Combined Cycle	Fleet Natural Gas
Combustion Turbine	Fleet Natural Gas
Distributed Generation	Solar Thermal
Fuel Cells	Onshore Wind
Nuclear Power	Existing Nuclear
Oil and Natural Gas Steam	Petroleum
Conventional Hydroelectric	Existing Hydro
Geothermal	Geothermal
Municipal Waste	Onshore Wind
Offshore Wind	Onshore Wind
Solar Photovoltaic	Solar Thermal
Solar Thermal	Solar Thermal
Wind	Onshore Wind
Wood and Other Biomass	Onshore Wind

EXHIBIT D-5. REGIONAL MARGINAL CAPACITY ADDITION GENERATION TECHNOLOGY MIXES

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
<b>U.S. Mix</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	51%	56%	59%	59%	57%	56%	54%
	Nuclear	0%	1%	1%	1%	1%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	27%	14%	11%	9%	7%	7%	7%
	Solar PV	21%	29%	28%	30%	34%	35%	38%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	1%	1%	1%	1%	1%	1%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Florida Reliability Coordinating Council</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	81%	21%	42%	47%	34%	41%	47%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	0%	0%	0%	0%	0%	0%	0%
	Solar PV	19%	79%	58%	53%	66%	59%	53%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Midwest Reliability Council</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	22%	44%	49%	52%	55%	54%	49%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	1%	0%	0%	0%	0%	0%	0%
	Wind	76%	54%	47%	44%	37%	33%	39%
	Solar PV	1%	2%	3%	4%	8%	12%	11%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Northeast Power Coordinating Council</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	79%	65%	58%	64%	67%	68%	68%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	16%	8%	11%	9%	8%	7%	8%
	Solar PV	3%	26%	31%	27%	25%	25%	24%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	2%	1%	1%	1%	0%	0%	0%

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
<b>Reliability First Corporation</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	71%	91%	92%	92%	91%	91%	90%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	24%	7%	6%	5%	5%	5%	4%
	Solar PV	5%	2%	2%	3%	4%	5%	6%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>SERC Reliability Corporation</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	55%	43%	56%	52%	50%	46%	44%
	Nuclear	0%	5%	4%	3%	2%	1%	1%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	1%	0%	0%	0%	0%	0%	0%
	Wind	23%	3%	2%	2%	1%	1%	1%
	Solar PV	19%	48%	38%	44%	47%	51%	54%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	3%	0%	0%	0%	0%	0%	0%
<b>Southwest Power Pool</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	6%	22%	21%	29%	29%	32%	29%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	94%	56%	29%	22%	16%	18%	16%
	Solar PV	0%	22%	49%	49%	54%	50%	55%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Texas Regional Entity</b>	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	56%	70%	74%	75%	76%	77%	64%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	14%	9%	8%	7%	6%	5%	4%
	Solar PV	30%	21%	19%	18%	18%	18%	32%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
Western Electricity Coordinating Council	Coal	0%	0%	0%	0%	0%	0%	0%
	Natural Gas	37%	46%	47%	52%	50%	51%	50%
	Nuclear	0%	0%	0%	0%	0%	0%	0%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	1%	1%	0%	0%	0%	0%	0%
	Wind	22%	16%	12%	11%	10%	10%	11%
	Solar PV	38%	34%	36%	31%	34%	34%	34%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	1%	3%	5%	6%	6%	5%	5%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%

\*Values for each region and year may not sum to 100% due to rounding

## D.4 NERC REGION ELECTRICITY CONSUMPTION MIX LCI DATA

The GWP data in **Exhibit 2-15** were developed using a combination of EIA data to determine the technology mix and NETL life cycle data to determine the associated GHG LCI. Data for projected electricity generation were developed using the reference case from the 2019 Annual Energy Outlook, specifically from the *Total Net Electricity Generation by Fuel* and *Renewable Energy Generation by Fuel* results sheets. [6, 24, 25] The Renewable Sources category in the *Total Net Electricity Generation by Fuel* data was replaced with disaggregated renewable data from the *Renewable Energy Generation by Fuel* data. Not all of the generation technologies presented in the AEO are available in the NETL Grid Mix Explorer, therefore some technology mapping was performed to provide an approximation of the GHG LCI (see **Exhibit D-6**). The assumptions made while mapping the technologies (stated below) are justified on the basis that they would not materially change the total GWP estimates for different regional grid mixes.

- “Biogenic Municipal Waste” and “Wood and Other Biomass” were mapped to “Other Renewables” because their individual contributions to the total capacity were very low. In the U.S. mix, the maximum capacity addition from biogenic municipal waste, and wood and other biomass was 0.49% and 0.36% of the total addition respectively. In the regional profiles the maximum capacity addition for these technologies were 1.85% and 1.75% of the total addition respectively.
- In the U.S. mix and most of the NERC regions, wind is the biggest renewable source in terms of contribution to the capacity addition, maximum for U.S. mix and the NERC regions being 8.8% and 36.7% respectively. Whereas, the “Other Renewables” category had a maximum contribution of 0.85% and 3.6% in the U.S. mix and the NERC regions respectively. In the absence of specific technologies in the NETL Grid Mix Explorer “Other Renewables” were mapped to “Onshore Wind” as a proxy.
- Both “Solar PV” and “Solar Thermal” are mapped to “Solar Thermal” in the grid mix explorer. This was done because of two reasons, the NETL Grid Mix Explorer consists of only “Solar Thermal” as a solar technology and the life cycle GHG impacts of solar PV and solar thermal are not substantially different relative to higher carbon technologies (46 and 36 g CO<sub>2</sub>e/kWh respectively). [32] Thus, the overall calculated life cycle GHG emissions impact for a regional grid mix would remain nearly the same whether or not the two technologies are combined.
- The EIA AEO technology has both offshore wind and wind (assumed to be onshore, since offshore is already segregated). Wind contributes to up to 8.8% to the total capacity addition in the U.S. mix and up to 36.7% in the NERC regions and offshore wind contribute only up to 0.004% and 0.05% to the total capacity addition in the U.S. mix and the NERC regions, respectively. Therefore, all wind technologies, offshore and onshore, are mapped to onshore wind technology in the NETL Grid Mix Explorer.

The resulting technology breakdown for makeup electricity generation is provided in **Exhibit D-7**.

#### EXHIBIT D-6. EIA TECHNOLOGY MAPPING - MAKEUP ELECTRICITY GENERATION TECHNOLOGY

EIA AEO TECHNOLOGY	NETL GRID MIX EXPLORER TECHNOLOGY
Coal	Fleet Coal
Distributed Generation	Solar Thermal
Natural Gas	Fleet Natural Gas
Nuclear	Existing Nuclear
Petroleum	Petroleum
Biogenic Municipal Waste	Onshore Wind
Conventional Hydro	Existing Hydro
Geothermal	Geothermal
Offshore Wind	Onshore Wind
Solar Photovoltaic	Solar Thermal
Solar Thermal	Solar Thermal
Wind	Onshore Wind
Wood and Other Biomass	Onshore Wind

#### EXHIBIT D-7. REGIONAL MAKEUP ELECTRICITY GENERATION TECHNOLOGY MIXES

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
<b>U.S. Mix</b>	Coal	26%	24%	24%	22%	21%	20%	19%
	Natural Gas	35%	37%	38%	39%	39%	39%	38%
	Nuclear	20%	16%	16%	15%	15%	14%	14%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	7%	7%	7%	7%	7%	7%	6%
	Wind	8%	9%	9%	9%	8%	8%	9%
	Solar PV	2%	4%	5%	6%	8%	10%	11%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	1%	1%	1%	1%	1%	1%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
<b>Florida Reliability Coordinating Council</b>	Coal	12%	17%	17%	16%	15%	14%	14%
	Natural Gas	72%	60%	60%	60%	52%	53%	54%
	Nuclear	13%	13%	12%	12%	11%	10%	10%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	0%	0%	0%	0%	0%	0%	0%
	Solar PV	1%	9%	9%	11%	21%	21%	21%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%
<b>Midwest Reliability Council</b>	Coal	44%	47%	47%	47%	47%	46%	43%
	Natural Gas	9%	9%	9%	9%	9%	10%	10%
	Nuclear	10%	3%	3%	3%	3%	3%	3%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	5%	5%	5%	5%	5%	5%	4%
	Wind	30%	34%	34%	34%	33%	33%	37%
	Solar PV	1%	1%	1%	1%	1%	2%	2%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%
<b>Northeast Power Coordinating Council</b>	Coal	2%	2%	1%	2%	2%	2%	2%
	Natural Gas	44%	49%	46%	50%	51%	51%	52%
	Nuclear	30%	24%	24%	19%	19%	19%	18%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	15%	16%	16%	16%	16%	16%	15%
	Wind	4%	4%	5%	5%	5%	5%	6%
	Solar PV	1%	2%	4%	4%	4%	4%	4%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	3%	3%	4%	4%	4%	3%	3%
<b>Reliability First Corporation</b>	Coal	34%	29%	29%	28%	27%	26%	26%
	Natural Gas	32%	42%	41%	44%	44%	45%	46%
	Nuclear	28%	24%	23%	23%	23%	22%	22%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	1%	1%	1%	1%	1%	1%	1%
	Wind	4%	4%	4%	4%	4%	4%	4%
	Solar PV	0%	0%	0%	0%	0%	0%	0%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%

REGIONS	TECHNOLOGY	2020	2025	2030	2035	2040	2045	2050
<b>SERC Reliability Corporation</b>	Coal	28%	26%	25%	22%	21%	20%	19%
	Natural Gas	37%	39%	41%	42%	41%	40%	39%
	Nuclear	28%	24%	23%	23%	22%	21%	20%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	3%	3%	3%	3%	3%	3%	3%
	Wind	1%	1%	1%	1%	1%	1%	1%
	Solar PV	1%	6%	6%	9%	12%	15%	18%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%
<b>Southwest Power Pool</b>	Coal	33%	38%	37%	33%	29%	27%	27%
	Natural Gas	26%	22%	17%	20%	21%	19%	16%
	Nuclear	4%	0%	0%	0%	0%	0%	0%
	Petroleum	2%	0%	0%	0%	0%	0%	0%
	Hydro	3%	4%	4%	3%	3%	3%	3%
	Wind	31%	35%	34%	33%	31%	32%	31%
	Solar PV	0%	2%	9%	11%	16%	18%	23%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Texas Regional Entity</b>	Coal	20%	18%	16%	12%	13%	12%	12%
	Natural Gas	50%	52%	55%	59%	60%	61%	56%
	Nuclear	10%	10%	10%	9%	9%	9%	8%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	0%	0%	0%	0%	0%	0%	0%
	Wind	16%	16%	15%	14%	14%	13%	13%
	Solar PV	4%	4%	4%	4%	4%	4%	11%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	0%	0%	0%	0%	0%	0%	0%
	Other Renewable	0%	0%	0%	0%	0%	0%	0%
<b>Western Electricity Coordinating Council</b>	Coal	19%	17%	15%	13%	12%	12%	12%
	Natural Gas	29%	26%	26%	27%	26%	26%	26%
	Nuclear	8%	7%	5%	5%	5%	5%	5%
	Petroleum	0%	0%	0%	0%	0%	0%	0%
	Hydro	26%	27%	26%	26%	25%	25%	24%
	Wind	8%	10%	10%	10%	11%	11%	12%
	Solar PV	6%	8%	11%	11%	13%	13%	13%
	Solar Thermal	0%	0%	0%	0%	0%	0%	0%
	Geothermal	2%	3%	5%	6%	7%	7%	7%
	Other Renewable	1%	1%	1%	1%	1%	1%	1%

\*Values for each region and year may not sum to 100% due to rounding

# APPENDIX E: NETL CO2U OPENLCA LCI DATABASE

The National Energy Technology Laboratory (NETL) has developed an extensive library of unit processes to model power generation and the associated supply chain. A relevant subset of that data is made available to principal investigators (PIs) in the **NETL CO2U openLCA LCI Database** including data on fuel production, fuel combustion, materials, transportation, electricity generation, and fossil power carbon dioxide (CO<sub>2</sub>) sources (see full list in **Exhibit E-1**). The PIs will be responsible for developing any missing data, with emphasis on the boundaries of their process. The following sections describe the approaches for doing so. See the **NETL CO2U openLCA LCI Database** unit processes for full metadata describing the assumptions and representativeness of each unit process.

## EXHIBIT E-1. LIST OF UNIT PROCESSES IN NETL CO2U OPENLCA LCI DATABASE

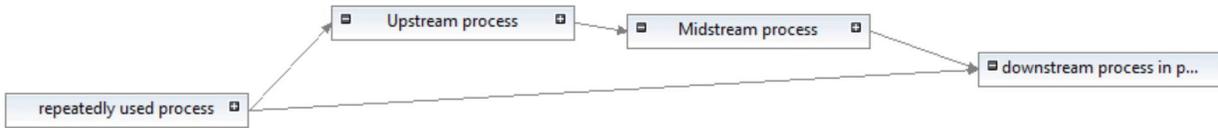
PROCESS CATEGORY	PROCESS NAME
<b>Fuel Production (excludes final combustion)</b>	Diesel Production
	Gasoline Production
	Natural Gas through Distribution – U.S. Mix
	Natural Gas through Transmission – U.S. Mix
<b>Fuel Combustion</b>	Combustion of Diesel
	Combustion of Gasoline
	Combustion of Natural Gas
<b>Material inputs</b>	Ammonia Production with Carbon Capture
	Ethanol Production, Dry Milling
	Hydrogen Production, Steam Methane Reforming
	Methanol Production from Natural Gas
	Concrete Production, 20 MPa
	Short Rotational Woody Crop Cultivation
	Steel Production
	Switchgrass Cultivation
	Urea Production
<b>Transportation</b>	Train Transport
	Ocean Freighter Transport
	Truck Transport
	CO <sub>2</sub> Transport, Pipeline
<b>Grid Electricity Generation</b>	U.S. Fleet Average Coal
	U.S. Fleet Average Natural Gas
	U.S. Fleet Average Fuel Oil
	U.S. Gen II Nuclear
	Solar Thermal
	Geothermal
	Hydropower Production
<b>Fossil Power Generation CO<sub>2</sub> Sources</b>	Onshore Conventional Wind
	NGCC Plant with Capture
	NGCC Plant without Capture
	SCPC Plant with Capture
	SCPC Plant without Capture
	SubPC Plant with Capture
SubPC Plant without Capture	

# APPENDIX F: NOTES ON READING THE OPENLCA CONTRIBUTION TREE

The contribution tree is a tool for structural path analysis. The tree displays the impact or inventory for every instance of every unit process along with the impact or inventory for every unit process upstream of it.

**Exhibit F-1** shows the openLCA model graph of a very simple product system, which will help to demonstrate how the contribution tree works.

**EXHIBIT F-1. A MODEL GRAPH OF A SIMPLE EXAMPLE PRODUCT SYSTEM**



To make the manual math simple, each unit process in the example product system emits 1 kilogram (kg) of carbon dioxide (CO<sub>2</sub>) and produces 1 kg of “product.” The resulting contribution tree for CO<sub>2</sub> inventory results is shown in **Exhibit F-2**.

**EXHIBIT F-2. THE CONTRIBUTION TREE RESULTING FROM THE EXAMPLE PRODUCT SYSTEM IN EXHIBIT F-1**

1	CONTRIBUTION	PROCESS	AMOUNT	UNIT
2	100.00%	downstream process in product system	5	kg
3	60.00%	Midstream process	3	kg
4	40.00%	Upstream process	2	kg
5	20.00%	repeatedly used process	1	kg
6	20.00%	repeatedly used process	1	kg

Note the quantities in the “Amount” column do not always refer to the amount of CO<sub>2</sub> resulting from just the unit process or instance of that unit process. Because all the links between products are 1 kg, after scaling, each instance of each unit process emits 1 kg of CO<sub>2</sub>. However, what’s being displayed in the “Amount” column is the direct emissions from the unit process in that row plus all emissions upstream of it. They are organized as the most downstream process (the one producing your functional unit) at the top, and each level appearing below it. The percent contribution appears in the next column to the right as you move further upstream in the product system. Thus, to understand the links between the unit processes, you must look through the position of the percent contribution. To understand which “repeatedly used process” is which, you must start at the percent contribution for the “repeatedly used process” you’re looking at and find which unit process has the percent contribution placed in the next column to the left and upward of it. That unit process is the one the “repeatedly used process” links to in the model graph. This is illustrated in **Exhibit F-3** using green arrows to show the links between the percent contributions.

**EXHIBIT F-3. CONTRIBUTION TREE FROM EXHIBIT F-2 WITH THE LINKS FROM THE MODEL GRAPH DISPLAYED IN THE CONTRIBUTION TREE**

1	CONTRIBUTION	PROCESS	AMOUNT	UNIT
2	100.00%	downstream process in product system	5	kg
3	60.00%	Midstream process	3	kg
4	40.00%	Upstream process	2	kg
5	20.00%	repeatedly used process	1	kg
6	20.00%	repeatedly used process	1	kg

These links are the key detail you need to understand if you are using the **NETL CO2U openLCA Results Contribution Tool** template to create the graphs. Additionally, if you want the direct emissions for every unit process, and not just those that are called out on the resulting graph, those are provided on each scenario sheet: **Column FE**, labeled “disaggregated totals,” provides those direct emissions for each instance of each unit process. Even though these calculations are done for you, an explanation of the math happening automatically in the contribution tree is provided below.

To demonstrate the math behind the percent contributions being displayed, **Exhibit F-4** provides the formula in absolute numbers and in cell references in brackets below the percent contribution. Each formula simply represents the “Amount” for that row divided by the total.

**EXHIBIT F-4. CONTRIBUTION TREE FROM EXHIBIT F-2 WITH THE UNDERLYING MATH FOR THE PERCENT CONTRIBUTION EXPLAINED IN FORMULAS IN BRACKETS**

1	CONTRIBUTION	PROCESS	AMOUNT	UNIT
2	100.00% [=5/5] [=F2/F2]	downstream process in product system	5	kg
3	60.00% [=3/5] [=F3/F2]	Midstream process	3	kg
4	40.00% [=2/5] [=F4/F2]	Upstream process	2	kg
5	20.00% [=1/5] [=F4/F2]	repeatedly used process	1	kg
6	20.00% [=1/5] [=F5/F2]	repeatedly used process	1	kg

The math underlying the “Amount,” displayed in brackets in **Exhibit F-5**, is more complicated and requires an understanding of the relationships between the unit processes. Also, the “direct emissions” are already known in this example because the example was designed to be so simple. In most models, the “direct emissions” need to be calculated based on the contribution tree. This calculation is performed automatically by the template.

**EXHIBIT F-5. CONTRIBUTION TREE FROM EXHIBIT F-2 WITH THE UNDERLYING MATH FOR THE “AMOUNT” EXPLAINED IN FORMULAS IN BRACKETS.**

1	CONTRIBUTION	PROCESS	AMOUNT	UNIT
2	100.00%	downstream process in product system	5 [=1+3+1] [=direct emissions + F3 + F6]	kg
3	60.00%	Midstream process	3 [=1 + 2] [=direct emissions + F4]	kg
4	40.00%	Upstream process	2 [=direct emissions + F5]	kg
5	20.00%	repeatedly used process	1 [=direct emissions]	kg
6	20.00%	repeatedly used process	1 [=direct emissions]	kg

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