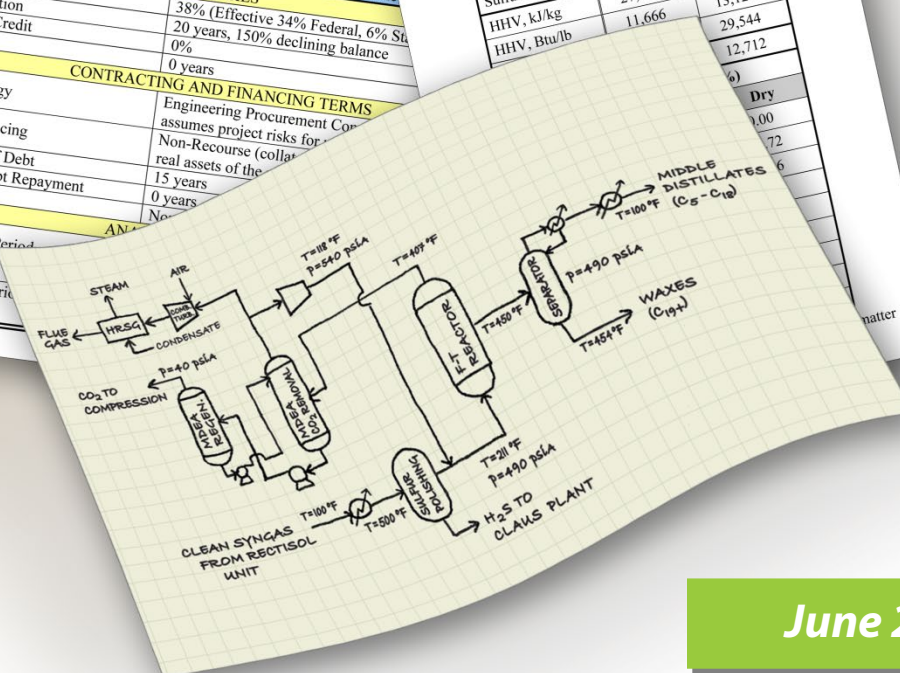


Performing a Techno-Economic Analysis for Carbon Conversion Technologies

Rank	Bituminous	
Seam	Illinois No. 6 (Herrin)	
Source	Old Ben Mine	
Proximate Analysis (weight %) (Note A)		
	As Received	Dry
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
	100.00	100.00
Total	2.51	2.82
Sulfur	27.113	30.506
HHV, kJ/kg		13,126
HHV, Btu/lb	11,666	29,544
		12,712



June 2023

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Quality Guidelines for Energy Systems Studies Performing a Techno-Economic Analysis for CO₂ Conversion Technologies

Final Report

June 8, 2023

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Acronyms and Abbreviations

AACE	AACE International	NETL	National Energy Technology Laboratory
atm	Atmosphere	NFPA	National Fire Protection Association
BEC	Bare erected cost	NOAK	N th -of-a-kind
CC	Carbon conversion	NO _x	Oxides of nitrogen
CCF	Capital charge factor	O ₂	Oxygen gas
CCUS	Carbon capture, utilization/conversion, and storage	O&M	Operating and maintenance
CEPCI	Chemical engineering plant cost index	OCM	Owner's cost or TOC/TPC cost basis multiplier
CHP	Combined heat and power	PC	Pulverized coal
CMV	Cumulative market value	psia	Pounds per square inch absolute
CO ₂	Carbon dioxide	Q _{NZCS}	Heat available from near-zero carbon energy sources
CO ₂ e	Carbon dioxide equivalent	QGESS	Quality Guidelines for Energy System Studies
CO ₂ C	CO ₂ conversion	R&D	Research and development
COP	Cost of product	RD&D	Research, development, and deployment
DCF	Discounted cash flow	RPP	Required purchase price
DOE	Department of Energy	s ⁻¹	Per second
EOR	Enhanced oil recovery	SC	Supercritical
EMB	Energy and mass balance	SSAE	Strategic Systems Analysis & Engineering
EPRI	Electric Power Research Institute	SMR	Steam methane reforming
FEP	Functionally equivalent product	SO _x	Oxides of sulfur
FOAK	1 st -of-a-kind	t	Tonne (1,000 kg)
gal	Gallon	TAG®	Technical Assessment Guide
GDPCTPI	Gross domestic product chain-type price index	TEA	Techno-economic analysis
h, hr	Hour	TFOM	Total annual fixed O&M
H ₂	Hydrogen gas	TG	Turbine generator
IOU	Investor-owned utility	TOC	Total overnight cost
ISO	International Organization for Standardization	TPC	Total plant cost
K	Kelvin	TRL	Technology readiness level
kcal/mol	Kilocalories per mole	TVOM	Total annual variable O&M
kJ/mol	Kilojoule per mole	U.S.	United States
kW	Kilowatt	y, yr	Year
lb	Pound	°C	Degrees Celsius
lb-mol/hr	Pound mole per hour	°F	Degrees Fahrenheit
LCA	Life cycle analysis	\$	U.S. dollars
MESA	Mission Execution and Strategic Analysis	\$/kW	Dollars per kilowatt
Mt/yr	Million tonnes per year	\$/MWh	Dollars per megawatt hour
MWh	Megawatt hour	%	Percent
N/A	Nonapplicable	ΔH ^o _{rxn}	Enthalpy change of the reaction
NEP	Notional energy penalty		

Glossary of Terms

Bare erected cost	The sum of material cost, labor costs, and equipment cost. Bare erected cost comprises the cost of process equipment, on-site facilities and infrastructure that support the plant, and the direct and indirect labor required for its construction
Block flow diagram	Diagram of a process including major unit operations and streams, including feeds and products, within the scope of the system
Capital cost	The cost of fixed, one-time expenses for the development of a plant such as the purchase of equipment, land, infrastructure, and the labor required for its construction.
Carbon management	Strategy to reduce emissions and meet climate goals by advancing low carbon and carbon-consuming technologies such as low carbon power generation and supply chains; carbon capture, conversion, and storage technologies; methane emissions reductions; critical mineral production; and CO ₂ removal
CO ₂ conversion	The transformation of CO ₂ into value-added products such as biofuels, chemicals, and building materials
CO ₂ conversion technology	A technology that converts CO ₂ into a value-added product
CO ₂ source	An existing CO ₂ -producing process or naturally occurring source of CO ₂ that can serve as a feedstock provider for a CO ₂ conversion technology
Consumable	Any material or chemical input to a process that must be continuously provided. Consumables may include feedstocks, sorbents, solvents, and catalysts
Co-product	One of the two or more products from a unit operation or system
Co-reactant	One of the two or more reactants entering a unit operation or system
Cost scaling	A cost estimation strategy in which existing costs or cost estimates for analogous or similar equipment are scaled based on a relevant process parameter (e.g., flow rates around equipment, auxiliary loads, utility requirements, etc.)
Emitter	A process or unit operation that emits greenhouse gases
Energy and mass balance	The calculation of all energy and mass flows to and from a process or between unit operations based on the conservation of energy and mass
Feedstock	Raw material fed to a process for conversion to products
Financial assumption	Expected or best guess values applied to financial parameters in the case of uncertainty regarding the true value of said parameter. Financial assumptions must be well-documented and justified
Fixed O&M cost	Operation and maintenance costs that are constant regardless of changes in external factors (e.g., labor costs, property taxes and insurance)

Greenfield plant	A new plant that is designed without prior construction or site constraints. A greenfield plant in this document refers to a new plant designed to redirect or capture the carbon dioxide from the flue gas for alternative use or geological sequestration
Operation & maintenance cost	The cost of recurring expenses for continued operation and maintenance of a plant. Operation and maintenance costs include the cost of raw materials, fuel, and other consumables; operating and maintenance labor; and waste disposal
Owner's cost	The total cost of bringing a plant to commercial operation not including the cost for engineering, procurement and construction; and process and project contingencies
Performance summary	Summary of major performance results from a complete performance model. The performance summary typically includes major flowrates including feed and product flowrates, utility requirements, and auxiliary loads
Performance model	A model of a process developed utilizing available tools/software that generates useful performance information about said process including an energy and mass balances and equipment performance based on design assumptions
Principal investigator	A head researcher of a CO ₂ C project under the U.S. DOE Carbon Conversion Program
Process assumption	Expected or best guess values applied to process parameters in the case of uncertainty regarding the true value of said parameter. Process assumptions must be well-documented and justified
Process contingency	The cost intended to compensate for the uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology
Process parameter	Any value that describes the performance of a unit operation of a process or the process as a whole. Process parameters include flowrates, efficiencies, auxiliary loads, heat and cooling duties, operating temperatures and pressures, and pressure drops
Project contingency	The cost intended to compensate for general uncertainty in cost estimates and potential risks in the development of a plant
Reference case	The chosen process, with accompanied performance model and cost estimates, that serve as a comparison to the novel technology process. Reference cases generally represent a conventional, commercial technology that produces the same product or products as the novel technology
Reporting metric	A standard of measurement reported as a result of a TEA
Researcher	A person working on research, design and development of the novel technology separate from those performing the associated TEA

Retrofit plant	An existing 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 plant that has been modified to capture the CO ₂ from the flue gas for alternative use
Sensitivity analysis	An analysis in which cost uncertainty is quantified by performing step-wise adjustments to key assumptions over a range of values. Sensitivity analyses can be performed on individual process parameters, equipment items, or the overall process costs
Stream table	A data table documenting information about each stream in a process including flowrate, composition, operating conditions (e.g., temperature and pressure) and energy flow
System boundaries	The process boundaries of a TEA scope ranging from inputs to outputs and including all intermediate unit operations that are considered in the performance model
Techno-economic analysis	A method of analyzing the technical and economic performance of a process, product, or service by systematically assessing technology states against a fixed reference case
TEA developer	A person developing the TEA separate from research, design, and development
Total overnight cost	The sum of total plant cost and all other “overnight” costs including pre-production costs, inventory capital, financing costs, and other owner’s costs
Total plant cost	The sum of bare erected cost; the cost of services provided by the engineering, procurement, and construction contractor; and all project and process contingencies
Technology readiness level	A system of ranking technology maturity, from conception to full deployment, developed by the National Aeronautics and Space Administration
Utility	Energy inputs to a process that are not directly converted to the product electricity, and heating and cooling loads
Variable O&M cost	Operation and maintenance costs that are dependent on external factors like market conditions, sales revenue, and output capacity (e.g., purchased electricity price, raw material price, etc.)

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1. Introduction

The Office of Fossil Energy and Carbon Management's (FECM) Strategic Vision: The Role of FECM in Achieving Net-Zero Greenhouse Gas Emissions describes FECM's role in advancing the Biden administration's goals of a fully decarbonized power sector by 2035 and net-zero economy U.S. greenhouse gas emissions by 2050 (facilitated by an interim goal of achieving 50-52 percent reductions by 2030 below 2005 levels). [1] The Biden administration's climate goals are further described in Executive Order 14008: Tackling the Climate Crisis at Home and Abroad which requires agencies to: 1) use the power of federal procurement and management of real property to support robust climate action and lead by example, 2) submit a Climate Action Plan that identifies agency climate vulnerabilities, steps to bolster adaptation, and increase climate resilience of facilities and 3) adhere to the requirements of the Made in America Laws in making clean energy, energy efficiency, and clean energy procurement decisions [2]. The Strategic Vision and climate goals enable the U.S. Department of Energy (DOE) to make strategic carbon management decisions, ensuring the use of fossil fuels in a climate-friendly context and designing a future that achieves and maintains net-zero greenhouse gas emissions. Specifically, FECM will accelerate capabilities for large-scale carbon dioxide (CO₂) conversion into value-added products that advance both net-zero emissions and justice goals, facilitated by markets for CO₂ as a feedstock. Additionally, FECM will help accelerate the path to a net-zero refinery, advance mineral carbonation approaches, and expand the availability of synthetic fuels.

The Carbon Conversion (CC) R&D Program, a part of the FECM Carbon Dioxide Removal and Conversion Division, supports innovative R&D that supports technologies that convert captured CO₂ from power and industrial sources into value-added products. The CC R&D Program primarily supports three CO₂ conversion pathways; mineralization, catalytic conversion, and biological uptake (mainly via algae) to produce products such as biofuels, chemicals, and building materials. A major tool required to evaluate and develop these technologies effectively is a techno-economic analysis (TEA). To ensure that technologies can be evaluated fairly and that project results can be compared across different technology pathways and product markets, a transparent and consistent method for the relevant technical and economic evaluations is critical. Standardizing assessment of CO₂ conversion (CO₂C) technologies will quantify economic viability before investing Federal funds in support of additional R&D. The wide variety of possible CO₂C pathways and products presents challenges for comparing technologies. Herein, this document expands on the prior 2014 CO₂C technology metric guidelines presented in the National Energy Technology Laboratory's (NETL) Cost and Performance Metrics Used to Assess Carbon Utilization and Storage Technologies and applies the principles of NETL's 2015 Quality Guidelines for Energy System Studies (QGESS): Performing a Techno-economic Analysis for Power Generation Plants ("TEA QGESS") to develop a framework for future assessments. [2, 3]

The assumptions and calculations outlined here and in the referenced documents provide a common basis to facilitate comparison between technology choices. Alternate approaches, perspectives, and assumptions may be standard in one industry (e.g., cement production) but not representative of other industries (e.g., algae), appearing reasonable on the surface but can significantly change the results of a TEA, and subsequent technology comparisons. The guidelines presented here are not intended to be used as a complete assessment for a specific technology approach, or for a process applied to a specific location or plant, which would require

far greater detail and site-specific information; these guidelines are intended to provide overarching guidance and remove uncertainty in the assessments to provide a transparent, reproducible, and comparable outcome. Deviations from the guidelines presented here, or situations not covered by these guidelines, must be explicitly stated by the TEA developer.

1.1. Background

Currently, no consistent methodology exists for evaluating CO₂C technologies within the DOE/FECM portfolio. Most studies use an adaptation of cost development and scaling documents for fossil-fueled utility sources, which have limited applicability to industrial or direct capture sources of carbon due to differences in CO₂ concentration, temperature, pressure, and trace species.

Metrics for cost and performance of the CO₂C system are available. Carbon capture, utilization/conversion, and storage (CCUS) research, development, and deployment (RD&D) metrics for screening multiple technologies have also been developed. [5] These are discussed in Section 2.5.

There are many potential CO₂C approaches that can be examined using TEA including:

- Catalytic conversion of CO₂ into fuels and chemicals
- Uptake of CO₂ into algae for bioproducts
- Mineralization of CO₂ into materials having economic value

The development of CO₂C processes involves numerous issues including:

- Cost-effective use of CO₂ as a feedstock for chemical synthesis
- Accounting for the source and cost/performance impacts of procuring H₂ or other reactants as required for the conversion process
- Accounting for the source, quantity, and cost/availability of electricity as required for the conversion process
- Integration of CO₂ into pre-existing products
- Efficiency (CO₂ integration reaction rate and the amount of CO₂ sequestered in a product)
- Rate, scale and quality of CO₂ as it relates to pressure, temperature, CO₂ concentration, and the presence of other components/impurities
- Market size of the end product

Furthermore, CO₂C processes involve issues to be addressed qualitatively including:

- Control/mitigation of contaminants
- Impacts on retrofit plants
- Development of a commercialization plan
- Flexibility issues
- Safety/environmental impacts
- Environmental justice

1.2. Types of Analysis

Two phases of screening analysis typically performed on developing technologies are defined below as Phase 1 and Phase 2 screening analyses. The overall TEA process is similar for both types of analyses. However, the level, quality, and accuracy of the information available for the screened technology will be more significant in a Phase 2 screening analysis than a Phase 1 screening analysis. Some studies may require a level of detail that falls between these two categories. In this case, the TEA developer must use their own judgment to plan the structure of the analysis, implementing aspects of both Phase 1 and Phase 2 screening analyses, as necessary. Exhibit 1-1 provides an example of potential delineation between Phase 1 and Phase 2 analyses to guide TEA developers and researchers in initial scope development when considering screening of a CO₂C technology. The table is not an exhaustive list of attributes of each phase, and it is not meant to be constrictive or expressly definitive. As mentioned, some studies may fall between the two phases (i.e., if performance data and process descriptions advance quickly ahead of available system cost data).

Exhibit 1-1. Description of Phase 1 and Phase 2 Screening Analyses

Parameter	Phase 1	Phase 2
TRL	Level 1 – Level 3	Level 3 – Level 4
Equipment Design	System description with: • Basic process concept description • Component descriptions • Partial to complete consumables list (including power users)	All of Phase 1 attributes, but with: • More defined process flow diagram(s) • Detailed component specifications • Consumable rates of use or narrow ranges for rates of use
Performance Data	• Feedstock data • Reaction conditions/expected conversion rates • Expected/target catalyst performance • Expected/target consumable costs/rates of use • Expected/target system performance	All of Phase 1 attributes, but with: • Specific operating conditions • Feedstock specifications • Feedstock and consumable rates • Reaction conditions/conversion rates from lab demonstrations • Catalyst performance data from lab demonstrations
System Costs	• Analogous equipment costs • Analogous catalyst costs (with notation of wholesale or small-scale pricing, as applicable) • Expected/target energy costs • Available/preferred process power sources (e.g., renewable only, on-site produced power, fossil-based)	All of Phase 1 attributes, but with: • Preliminary equipment and catalyst costs • Energy consumption from lab demonstrations • Expected catalyst lifecycle data based on lab demonstrations
Barriers to Advancement	• Current hold points or research gaps • Competing production technologies and their commercial outlooks • Equipment cost or material/consumable availability constraints • Commercial investment outlook(s) • Marketability of end product	
Advantages/Disadvantages over Comparable Conventional Technologies	• CO₂ available for capture from conventional producer (for relating utilization/conversion potential to an existing emitter) • Conventional capture costs at competing producer • Low-cost drivers for either technology • Current state-of-the-art for decarbonization of competing technology • Production rate relative to amount of energy used	

1.2.1. Phase 1 Screening Analysis

The objective of a Phase 1 screening analysis is to use general engineering judgment to determine the potential of the screened technology to meet RD&D goals and demonstrate economic viability. A literature review shall be conducted to document the competing conventional technology and potential advantages and/or disadvantages of the CO₂C technology. Furthermore, a TEA shall be completed, to the extent possible, using data from preliminary RD&D and literature search as well as assumptions based on best engineering judgment. All assumptions and methods of calculation shall be documented and clearly defined.

In a Phase 1 screening analysis, information (i.e., the details described in Exhibit 1-1) on the screened technology is limited. In the event that necessary data is unavailable, well-defined assumptions may be made using cost and performance for similar technologies available in previous studies or public literature or best engineering judgment. The result of a Phase 1 screening analysis must provide a narrative based on evaluation, whether qualitative or quantitative, describing the potential of the screened technology to meet RD&D goals with further development. If the results affirm the screened technology's potential to meet RD&D goals, a Phase 2 screening analysis may be completed assuming that the information necessary for a Phase 2 screening is available.

1.2.2. Phase 2 Screening Analysis

The objective of a Phase 2 screening analysis is to determine the potential of the screened technology to meet RD&D goals and demonstrate economic viability with a more rigorous and comprehensive evaluation than is possible in a Phase 1 screening analysis. In addition to the components of a Phase 1 screening analysis described in Section 1.2.1, a Phase 2 screening analysis shall include a comparison of current or projected techno-economic performance of the screened technology to benchmarks, such as state-of-the-art technology or process alternatives, and RD&D goals.

In a Phase 2 screening analysis, information on the screened technology is more readily available than in a Phase 1 screening analysis. The exact scope of available information is dependent on the status and progress of research efforts, but must exceed that of a Phase 1 screening analysis, as illustrated in Exhibit 1-1. The results of a Phase 2 screening analysis shall describe a more refined and technically-specific process to approach RD&D goals with further development. This specificity may include performance metrics that must be achieved by a material or process, cost targets to elucidate or achieve, or other measurable data not subject to interpretation or projection.

1.3. Requirements for Techno-Economic Analysis

The primary requirement for a TEA is a well-defined system concept. Results of a TEA will be increasingly informative with increasing technical design data. The objective of the technology must be clearly defined, with supporting references for design assumptions and target performance and/or cost metrics. To fully realize the benefits of a TEA, developers are encouraged to consider and present a system that can be scaled to commercially relevant sizes (i.e., current testing may be at the gram scale; however, the system configuration must apply gram-scale results to project an industrial-sized process).

1.3.1. Starting Point for Evaluation

The starting point for TEA on CO₂C technologies is the selection of a CO₂ feedstock source. CO₂ can be provided to the CO₂C process via plant flue gas streams or from CO₂ capture or removal systems. Potential CO₂ sources include power plants, industrial sources, and direct air capture plants. Depending on the selection of CO₂ source, a price must be attributed to the feedstock. In lieu of a specific, justifiable price, feedstock price may be estimated and considered a sensitivity parameter. Furthermore, the CO₂C system boundaries (i.e., the scope of the analysis ranging from process inputs to outputs) must be clearly defined. For example, the TEA developer must describe the process conditions of the feedstock and whether it requires compression/cooling/heating/etc. More information related to feedstock characterization is available in the TEA QGESS. [4]

NETL's *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity* (Fossil Energy Baseline) and *Cost of Capturing CO₂ from Industrial Sources* reports provide a consistent and transparent design basis and analysis methodology, and can be used as a potential starting point for CO₂ sourced from power plants. Relevant cases are listed below in order of highest-to-lowest purity CO₂ stream.

- Case B12B (supercritical [SC] pulverized coal [PC] plant with 90 percent solvent-based post-combustion CO₂ capture): provides a pure CO₂ product stream for a standalone, conversion only technology
- Case B31B (natural gas combined cycle plant with 90 percent solvent-based post-combustion CO₂ capture): provides a pure CO₂ product stream for a standalone, conversion only technology
- Cement Plant Industrial CO₂ Capture Case (off-gas from a cement kiln with 90 percent solvent-based post-combustion CO₂ capture): provides a pure CO₂ product stream for a standalone, conversion only technology
- Cement Plant Industrial Case (off-gas from a cement kiln without capture): provides a reference case for a greenfield industrial plant if capture is an integral part of the CO₂C technology (or if CO₂ can be used directly from the process emissions stream)
- Case B31A (natural gas combined cycle plant without capture): provides a reference case for greenfield power plants if capture is an integral part of the CO₂C technology (or if CO₂ can be used directly from the flue gas)

If the technology to be evaluated has specific application to industrial sources (i.e., there are system integration opportunities that only exist at a steel plant or refinery, or a project has pre-selected an industrial source to serve as a host site for future demonstration), then the CO₂ source must be specified to accurately quantify the concentrations of feedstock components. For retrofit applications, considerations must also be given to the availability of space. Guidance on retrofit difficulty for amine-based post-combustion CO₂ capture systems was evaluated in NETL's *Retrofit Cost Analysis for Post-combustion CO₂ Capture*. [6] Based on engineering judgment, similar retrofit difficulties may be estimated for CO₂C technologies, or in lieu of detailed retrofit difficulty considerations, a retrofit factor may be applied to total plant costs—estimated based on QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance (Cost Estimation Methodology QGESS) methodology—and considered a sensitivity parameter for the study. [7] In addition to retrofit difficulty, if land must be purchased to accommodate the addition of a CO₂C technology, land costs must be included in the TEA.

Regardless of the CO₂ source, the concentration, scale, rate, and purity requirements for the inlet to the CO₂C system must be clearly specified. Similarly, CO₂ feed temperature and pressure requirements of the CO₂C system must be identified. The CO₂C plant must include all processing equipment required to achieve the CO₂ purity requirements or to meet pressure and temperature requirements, unless the CO₂ source is provided at conditions immediately suitable for the CO₂C system.

Researchers often do not have access to industrially sourced CO₂, and laboratory tests often use pure CO₂ feedstocks that don't reflect the composition of process sourced CO₂. If possible, contaminant testing or proxy test results shall be considered within the research plan and results communicated with TEA developers. The assumptions and data gaps regarding the feedstock CO₂ requirements must be documented in the TEA.

1.3.2. Process and Product Definition and Description

The CO₂C technology must be defined and described as completely as possible including all feeds, reagents, products, processes, and unit operations required in the integrated CO₂C process. The current market for the CO₂C technology generated products (prices, market size, geographic distribution, etc.) must be discussed. More information is available in Section 3 of the TEA QGESS [4], and existing NETL reports—including the Fossil Energy Baseline—can be used for examples of typical assumptions and data sources. [8]

1.3.3. Performance Data/Parameters

All performance data and modeling parameters must be defined and included where possible. This includes data based on the current RD&D status as well as projected values for modeling data, which may require literature searches or requests for information from equipment vendors. Frequent communication with RD&D researchers must be maintained as ongoing tests may produce results that impact design assumptions. Research gaps and levels of uncertainty must also be clearly identified as this information can inform sensitivity ranges. In lieu of research-backed levels of uncertainty, sensitivity ranges for design assumptions may be established using AACE International (AACE) guideline uncertainties at the class level appropriate to the analysis. [9] The expected material input flows and energy input flows (including power, steam, process water, chemical reagents, and cooling water) for the commercialized technology must be included along with the expected source (e.g., power purchased from grid, new auxiliary combined heat and power [CHP] plant, existing adjacent cooling tower, municipal/well water).

A energy and mass balance (EMB) is useful for determining performance and cost metrics and must be included in Phase 2 screening analyses. EMBs can be based on a theoretical model using literature data, bench-scale lab data, or pilot testing data. If it is determined to be prohibitively time-consuming to develop an EMB for a Phase 1 screening analysis, block flow diagrams (BFD) and stream tables can be developed as an alternative.

1.3.4. General Economic Assumptions

Current market prices for feedstocks and technology generated products, as well as estimates of availability and demand, can be based on literature reviews and vendor information, if available. Market data must be collected from high quality sources and represent a time frame that is relevant to the analysis. If the technology is expected to enhance or replace an existing process,

the current capital, operating costs, and capacity factor (percent of operating hours per year) for the existing process can be a source for economic assumptions. As it is often difficult to determine accurate costs for novel equipment, using costs for the existing process as a close proxy (with contingency) may be a suitable cost estimation approach. All economic assumptions (e.g., feedstock price, financial factors, purchased power or fuel prices) should be evaluated as individual sensitivity parameters, and in some evaluations, consideration of the effects of varying assumptions cumulatively may be appropriate.

General cost estimating and economic assumptions specifically applicable to the CO₂C technology such as size restrictions (e.g., modular or scaled to fit), location restrictions (e.g., water availability, feed source, variable feed rates due to load following, temperature limitations), or labor restrictions must also be discussed. For retrofit cases, existing plant costs can be considered as sunk costs. Disposal costs, assumptions, and environmental impacts for any generated wastes must also be discussed.

All inputs to the system must be known or assumed with the level of detail required by the chosen screening analysis type (including the basis with references) and have a specified source. H₂, O₂, steam, electricity, or other process consumables must all have required amounts (derived from the mass balance) and have a specified source (purchase over the fence from a supplier, on-site air separation unit, extracted from the steam cycle of a power plant, steam methane reforming [SMR] on-site, etc.) The process assumptions for providing consumables can be varied across cases if desired. For example, one case may evaluate purchased H₂ over the fence at a current market price (with references), whereas a second case may include an SMR in the plant performance, capital cost, and the operating and maintenance (O&M) costs and present a case where H₂ is generated on-site.

Cost estimation methods must be specified in detail with all assumptions and data sources stated clearly. The Cost Estimation Methodology QGESS can provide guidance on specific assumptions typical to NETL studies. [7] Cost metrics must be calculated based on data provided in the cost estimate. If a developer is not sure how to develop capital and operating costs for their system, the NETL baseline series of reports is one of many references available in the literature to provide these cost references. In addition, the Capital Cost Methodology QGESS can provide guidance on how to use these cost references and adjust the capital estimate to fit that required by the CO₂C technology under consideration.

1.4. Recommended References

The following is a list of references produced by NETL and other organizations that may serve to inform development of the CO₂C TEA.

1. NETL's QGESS: Performing a Techno-Economic Analysis for Power Generation Plants, 2015 [4]
Provides guidance including typical assumptions and metrics for comparing power plant projects.
2. NETL's QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance, 2019 [7]
Presents financial parameters selected for investor-owned utility applications used for NETL system studies.

3. NETL's Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Revision 4, September 2019 [8]
Provides helpful examples including references for CO₂ feed stream data and can be used as a cost reference for similar type equipment. Other volumes in the NETL Baseline series can be used for alternative locations and coal types if needed.
4. NETL's QGESS: Capital Cost Scaling Methodology, 2019 [10]
Presents cost scaling methods used for NETL system studies.
5. NETL's QGESS: Process Modeling Design Parameters, 2019 [11]
Presents modeling parameters and assumptions used for NETL system studies.
6. NETL's QGESS: Carbon Capture Retrofit Studies, 2019 (pending) [12]
Summarizes additional considerations and factors to apply in post-combustion capture retrofit studies beyond those covered in the Cost Estimation Methodology QGESS. For CO₂C retrofit scenarios, the overarching guidance provided in this QGESS would also be applicable to these types of cases.
7. NETL's QGESS: Estimating the Future Cost of Advanced (Pre-commercial) Technologies and Plant Designs, mid-2020 (pending) [13]
Describes the approach favored by DOE/NETL to improve the clarity and consistency of "*Nth*-of-a-kind" (NOAK) cost estimates for advanced technologies. To assess the viability and competitiveness of a new technology, a common figure of merit is its expected future cost at commercial scale once it is widely deployed. This cost is commonly referred to as the NOAK cost. Such costs may be sought for a single technology component (such as an advanced carbon capture and storage process) as well as for an integrated plant employing one or more advanced components. At present, methods and assumptions for estimating NOAK costs vary widely.
8. Global CO₂ Initiative: TEA and LCA Guidelines for CO₂ Utilization, 2018 [14]
Describes the process of setting up a TEA from scope to uncertainty analysis, segmented by the audience perspective (RD&D, corporate, policy), but does not provide information on how to approach cost estimation.
Includes worked examples to show application of principles outlined.
9. Carbon Capture and Utilization RD&D Metrics Design, 2017 [5]
Provides perspectives on carbon capture and conversion RD&D and identifies metrics that may assist DOE or others to specify overarching RD&D objectives, identify technology areas of interest, and evaluate specific technologies and projects.
10. NETL CO₂C LCA Guidance Toolkit [15]
Provides a framework (including a guidance document, software, parameter database, and other support tools) for principal investigators within the CO₂C program to complete a life cycle analysis (LCA) and defines specific scenarios to be used for all LCAs (for example, if power is assumed to be sourced from the grid, use this CO₂e factor; if sourced primarily from renewables, use this CO₂e factor).

2. Techno-Economic Analysis Approach & Recommendations

This section includes more detailed information on what to include in a TEA on CO₂C technologies and how to estimate/calculate it. More general advice can be found in the TEA QGESS. [4]

2.1. Proposed Process Description

When performing a TEA on CO₂C, it is important to understand the essence of that CO₂C technology or process. The CO₂C technology must be defined and described as completely as possible. The following questions can help with the definition.

- What reactions are involved?
- What are the reactants and co-reactants and what is their source?
- What are the products and co-products?
- What are the reaction conditions?
- What are the heats of reaction?
- What catalysts and co-catalysts are required?
- What are the pre- and post-processing steps required to meet feedstock and product purity requirements?
- Where are the system boundaries drawn?
- Is the system batch, periodic, or continuous?
- At what scale has the technology or process been demonstrated?
- What are the environmental and safety concerns?

In cases where the new CO₂C technology or process, also referred to as pathway, competes with an existing or traditional non-CO₂C pathway for the product of interest, it is important to understand all the pertinent details of the traditional pathway, because some metrics compare the new pathway benefits relative to the traditional one.

The performance of the technology can be defined by answering questions such as

- What is the conversion efficiency or yield of each reaction at the specified reaction conditions?
- What is the overall mass and energy balance, including pressures, temperatures, flow rates, and compositions, based on a defined process flow diagram, for the system being evaluated?
- Has the technology or process been assessed as an integrated system, including any recycle streams, heat integration, and intermediate and/or final separation of products to meet specified product purities?
- What is the consumption rate and useful life of any catalysts/co-catalysts?

- What are the effects of contaminants in feedstocks on the catalyst performance and/or life (e.g., water content, trace species, other impurities)?
- What is the intermittent or continuous rate of any purge or waste streams and are these streams hazardous materials?
- If the new process is replacing an existing process, what are the above parameters for the existing process?

The economics of the process can be assessed by answering questions such as

- What market does the process product target, and what is the size of the market?
- What are the unit and total costs of all the material (feedstocks) and energy inputs at the conditions required by the process at the system boundary? The market factors (e.g., location, year) must be specified for each of the costs.
- What is the availability of all material feedstocks required?
- What are per unit and total costs (or values) of all the material and energy outputs, including any waste streams, at the system boundary?
- What are the capital costs of all the equipment specified within the system boundary?
- What are operating costs of the process as specified within the system boundary?
- What is the reactor volume required for the scale of the process?
- What is the plot space required for the scale of the process?
- What are the known hazards, and what are the likely safeguards?
 - Are any of the non-product system output streams considered hazardous waste?
 - If so, how will they be disposed of, and at what price?
- If the new process is replacing an existing process, what are the above parameters for the existing process?

For any analysis, it is important to define the boundaries of the study. Questions to be answered when considering the boundary definition of the study are as follows:

- Do the assessment bounds include applying capture to a reference plant?
- Will the study assume a purchase price of CO₂?
 - If so, a sensitivity study on the assumed CO₂ purchase price is recommended.
- Or will the study calculate an allowable CO₂ purchase price based on the CO₂C technology performance and cost?
 - An allowable purchase price is defined as: price at which the CO₂C technology can purchase CO₂ such that the CO₂C technology product can be produced and sold at the current market price for that product.
 - This approach requires a complete process definition, performance, and capital cost estimate.
- Or, is the CO₂C technology so novel and undeveloped that the best approach is to consider marginal cost increases against the target products current market price? (This

would draw bounds around the most mature pieces of technology within the CO₂C technology itself that could have their performance and cost estimated.)

- An example would be where a CO₂C technology requires pressurization of the inlet CO₂ reactant, but the balance of the system is sufficiently defined for TEA. The power requirement and capital cost of pressurization could be calculated per unit of CO₂C technology product expected, and reported as a percent increase to the current product market price.
- Will other process inputs be made on site within the project battery limit (H₂ and O₂, e.g.) or procured over the fence?
- Will the process be self-sufficient with respect to utilities like steam, water (cooling and process), and electricity, or will there be an external source and at what cost?

Other issues that should be considered are project and process dependent and include the following:

- Technology readiness level (TRL) of key equipment items and the overall process
- Existing commercial process (status, description, size)
- Expected size of market for CO₂C product (U.S. and worldwide)
- Dispersed versus concentrated market including transportation impact
For example, cement plants are dispersed throughout the U.S. due to cost to transport cement. Concentrating 100 percent of U.S. cement production at a single 650 MW power plant may not be feasible due to transport logistics and costs.
- Pipeline supply pressures relative to technology pressure requirements.
For example, a technology that requires CO₂ at a low pressure would necessitate additional capital and operating expenditure if integrated with a high-pressure CO₂ pipeline. Alternatively, integration with the CO₂ outlet of a capture unit at a power plant would avoid additional costs associated with compression, transportation, and pressure reduction.
- Safety/environmental concerns (if any)
- Chemical/material hazards
The scale of the National Fire Protection Association (NFPA) “fire diamond” is that as the value increases from “0” to “4,” the relative hazard increases from “none” to “severe”
- Pressure safety system integration
- Operating and maintenance procedures
- Waste disposal and water treatment considerations
- Hazardous vent and blowdown streams

Data gaps can be filled by performing literature searches for information on similar processes, products, and applications. Specific vendor requests for information may be required. The NETL modeling and scaling guidelines can be used for similar equipment even in non-power generation processes if similar conditions exist. [10, 11] Engineering handbooks and design textbooks are also a good source of initial information on proposed designs. [16, 17] Commercial software is available to support cost estimating.

2.2. Design Basis and Assumptions

The design basis and all process and economic assumptions for a TEA of any technology should be documented as completely as possible. Exhibit 2-1 is an example of information that should be collected at the start of a CO₂C technology TEA.

Exhibit 2-1. Design basis data table example

Project Name	Example Entries
Principal Investigator/Partner	ABC University/XYZ Laboratory
RD&D Goal	Find catalysts to enable the CO ₂ C pathway
RD&D Status	Catalysts reduce the activation energy and promote the reaction, but the conversion rate is very slow
CO ₂ Conversion Product	Acrylates: acrylic acid (C ₃ H ₄ O ₂) and acrylic acid derived salts & esters (i.e., sodium acrylate [C ₃ H ₃ NaO ₂])
Capture/Conversion	Conversion only
CO ₂ Source	Relatively pure CO ₂ source, post-CO ₂ capture (impurities may impact catalyst performance)
Conversion Pathway	Reaction pathway defined: one-step catalytic reaction
RD&D Conversion Feedstock	Ethylene (C ₂ H ₄)
Conversion Reaction	C ₂ H ₄ + CO ₂ → C ₃ H ₄ O ₂
Reaction Conditions	23°C, 1 atm, 1:1 ethylene to CO ₂ molar ratio
Rate Constant	3.8(3)×10 ⁻⁵ s ⁻¹
Activation/Reaction/Other Energy	ΔH = 24(3) kcal/mol, ΔS = 1(8) kcal/mol K
Size of Market for Conversion Product	U.S. market: \$1.2–1.5 billion/yr for acrylic acid and acrylic acid-derived esters (vendor data) Worldwide production: 2–8 Mt/yr CO ₂ C
New Pathway CO ₂ Emission	No CO ₂ produced in reaction stoichiometry; side products (CO ₂) avoided
Price of RD&D Feedstock	\$1,100/ton; price in U.S. is expected to decrease with increasing natural gas production
Availability of RD&D Feedstock	30 Mt/yr (U.S. capacity 2009); 120 Mt/yr (World capacity 2008). Availability in U.S. expected to increase with increasing natural gas production
Price of Conversion Product	\$1,300–1,500/ton acrylic acid (vendor data) (\$1,400/ton average)
Energy Reduction over Traditional Pathway	N/A
CO ₂ Emission Reduction over Traditional Pathway	1 mol acrylic acid : 0.7 mol CO ₂ for traditional process reduced to zero
Conversion Assumptions	N/A
Other Data	N/A

Project Name	Example Entries
Traditional Pathway Feedstock	Propylene (C ₃ H ₆)
Traditional Pathway Reactions	(1) C ₃ H ₆ + O ₂ → C ₃ H ₄ O + H ₂ O; (2) C ₃ H ₄ O + ½O ₂ → C ₃ H ₄ O ₂
Traditional Pathway Reaction Conditions	(1) 370°C; (2) 270°C
Price of Traditional Feedstock	25–50% higher cost from above for propylene (C ₃ H ₆)
CO ₂ Emission	Undesired side reactions produce CO ₂ for traditional process. Example process distribution given as 1 mol acrylic acid : 0.7 mol CO ₂

2.2.1. Global Assumptions

The NETL baseline reports can be used as sources for typical assumptions applicable to TEAs. Site characteristics (e.g., location, topography, acreage, transportation, water availability, climate) and site ambient conditions (e.g., elevation, air temperature, pressure, cooling water temperature, International Organization for Standardization [ISO] conditions) are addressed. [8] For cases where a research project has identified a specific site for consideration, it is recommended that cases be developed for both the existing site and the baseline ISO conditions. Development of an ISO condition case allows for simpler technology comparison across research projects, and technology types. The NETL QGESS reports provide guidance on methods, and the publicly available references used, to develop site conditions for use in TEA for existing sites other than ISO conditions. [11]

2.2.2. Technology CO₂ Source Requirements

As described previously, CO₂ can be provided to the CO₂C process via plant flue gas streams or from CO₂ capture or removal systems. Capture and conversion technologies can either use flue gas directly from a power plant without purification or can include an integrated capture component, while strictly CO₂C technologies require a purified CO₂ stream.

Questions to be answered to fully characterize CO₂ sources are as follows:

- What purity of CO₂ is present in the available feed stream and what purity does the CO₂C technology require?
- Will contaminants (SO_x, NO_x, particulate matter, heavy metals, other) impact system performance, and does the CO₂C technology require secondary CO₂ reactant stream purification to mitigate contaminant performance impacts?
 - An analogous example would be a CO₂ capture amine requiring low inlet sulfur concentration to avoid solvent degradation. In this instance, flue gas leaves the flue gas desulfurization still containing ppm levels of SO₂, and the first step of the amine solvent capture system may be to scrub the flue gas to lower SO₂ levels before the flue gas contacts the solvent.
- What are the pressure and temperature of the available feed stream and what conditions are needed for the CO₂C technology?
- How much water is present in the available feed stream and how much can be tolerated by the CO₂C technology?

- How much oxygen is present in the available feed stream and how much can be tolerated by the CO₂C technology?

2.2.3. Pipeline Quality CO₂

The baseline studies can be used as sources for CO₂ feedstock assumptions. Stream 29 in the block flow diagram for NETL's Fossil Energy Baseline report (Fossil Energy Baseline Case B12B) is the captured CO₂ stream at low pressure (prior to compression) that would be available to the CCUS technology, and includes composition, properties, and conditions. [8] Note that the pressure and temperature of this stream are 28.9 psia and 86°F, respectively. The composition of Stream 29 shows that it is 98.6 mole percent CO₂, with the only other component being water vapor at 1.4 mole percent. Other components may be present in trace quantities.

The CO₂ feedstock should be priced according to CO₂ capture and transportation costs presented in the baseline reports.

2.2.4. Partially Concentrated CO₂

If the required purity of the feedstock CO₂ can be lower than the product streams from the baseline report, then the baseline report values can still serve as an upper bound to the price. There may be additional issues to consider when transporting the feedstock via pipelines if it is not high purity CO₂. Accordingly, processes combining capture with conversion may have to be located on site with the CO₂ source plant.

2.2.5. Direct Use of Flue Gas

Flue gas should be considered a free feedstock. However, additional flue gas ducting will need to be installed and additional compression may be required, and the CO₂C plant will have to be installed on site with the power plant (or another CO₂ source plant). Other equipment such as fans, compressors, cooling systems, etc., depending on the feedstock conditions required by the CO₂C technology, will need to be included in the total system capital cost reported.

2.2.6. Other Consumables/Fuel (Type, Source, and Quantities)

Data and assumptions concerning other consumables and fuels required by a CO₂C process can be obtained from vendors or via literature searches. Previous NETL studies are a good source of information on consumables and fuels typically used by NETL for energy-related studies. [8] Requests for information from current vendors and literature searches can provide data on current market availability and demand as well as current market prices.

2.2.7. End Use (Product or Permanent Storage)

Assumptions pertaining to the final disposition of the CO₂ need to be defined as completely as possible. If the final disposition of CO₂ is permanent storage, as described in DOE's Carbon Negative Shot which aims to remove gigatons of CO₂ from the atmosphere and durably store it for less than \$100 per ton of net CO₂-equivalent, does it require monitoring to ensure the storage remains permanent? [18] If a product that is currently commercially available is generated, what is the impact of the CO₂C process on the quality of the product and how will this process impact the existing market now and in the future? Requests for information from current vendors and

literature searches can provide data on current market availability and demand as well as current market prices.

2.2.8. Auxiliary Power Requirements (Source and Quantities)

The source of any power required by the CO₂C process for fans, pumps, compressors, etc. should be specified. A CO₂C process attached directly to a power plant may be able to extract power from the plant's generator. In this case, presentation of the power plant's post-CO₂C technology efficiency, and cost of electricity requirement, is highly relevant to the results so as to frame the global impact on the system. A stand-alone CO₂C process plant could include a natural gas turbine generator, a renewable power generator, or purchase power from the grid. If a renewable source is assumed, the capacity factor may be limited to operating only when the renewable energy is available. This may be acceptable if the process operates in a batch mode or only periodically, but a backup source should be specified if it operates continuously at steady state mode. The quantity of power required may dictate the potential sources feasible for consideration. Small quantities could easily be purchased but larger quantities may need on-site sources. Modeling can be used to determine the power requirements. The NETL process modeling guidelines provide data typically used in NETL studies. [11]

If some of the TEA focus is on renewables, identify what the capacity factor would need to be to produce a competitive product (selling price) when using low cost/free electricity. If needed, include capital/O&M cost for energy storage such that high-capacity factors can be achieved.

2.2.9. Heat and Cooling Requirements (Source, Quantities, Quality, and Conditions)

Any external source of steam or heat required by the CO₂C process for heat exchangers or reactors should be specified. A CO₂C process attached directly to a power plant may be able to extract steam from the plant's steam cycle, but this could result in a derate of the plant's generation, which should be included in the TEA calculations, similar to the approach suggested for power extraction from the existing power plant. A stand-alone CO₂C process plant could include a steam boiler or CHP plant. The quantity and quality of the steam required may dictate the potential sources. Modeling can be used to determine the steam requirements. The NETL process modeling guidelines provide data typically used in NETL studies. [11] If an existing plant is derated, then a source and price for makeup power should be included in the economic assessment. This guidance only applies if a CO₂C technology requiring steam for heat is coupled with a power generation plant or with a plant that produces on-site power with a steam turbine. The capture system retrofit guidelines provide information on derate calculations and assumptions typically used in NETL studies. [13]

Cooling required by the CO₂C process for heat exchangers or reactors should be specified. A CO₂C process attached directly to a power plant may be able to extract cooling water from the plant's cooling tower if available, and the approach suggested for power and steam extractions from the existing power plant should be incorporated. If more substantial cooling is required, a refrigeration system may need to be included. A stand-alone CO₂C process plant could include a stand-alone cooling tower or refrigeration unit. The quantity and quality of the cooling required may dictate the potential sources. Modeling can be used to determine the cooling requirements. The NETL process modeling guidelines provide data typically used in NETL

studies. [11] Requests for information from current refrigeration unit vendors and literature searches can provide data on commercial systems.

2.2.10. Water/Air Requirements (Source, Quantities, and Conditions)

Water quality and availability, as well as air composition are site dependent. Unless a specific location is defined for the CO₂C technology, the NETL guidelines and baseline assumptions can be used. [4, 8]

2.3. Performance Analysis

The guidelines on TEA for power generation provide a comprehensive list of considerations and assumptions that can also be applied to CO₂C technology evaluations. [4] A typical TEA includes a reference case and subsequent cases that involve variations of the reference case. For example, the reference case could be an existing commercial process generating a product with the subsequent cases including the CO₂C technology generating the same product based on varying assumptions. In another example, the reference case could represent the CO₂C technology operating with grid-sourced electricity, and a subsequent case could incorporate the performance and cost impacts of generating the electricity requirement onsite with a purchased combustion turbine.

A process model can be used to calculate performance results based on the assumptions discussed in the previous section. The model may consist of a simple spreadsheet with basic engineering formulas or a complex detailed model, such as an EMB, using commercial process simulation software. Typical input data for the model may include the following:

- Site/location conditions/ISO default assumption
- Feed/product/other purity specifications
- Feed stream flows and process conditions
- Conversion/usage
- Heat duties
- Rate constants
- Emission potential and controls

All references and data sources (such as engineering judgment, laboratory results, plant operating data, or vendor quotes) should be listed in the TEA report for all model input data.

The TEA should include results in such a form and level of detail sufficient to facilitate a meaningful technical analysis of the advanced technology. [4]

For each case, the TEA should include

- Block flow diagram and accompanying stream tables
- Performance summary
- Air emissions tables
- Carbon, sulfur, and water balances as applicable
- Itemized major equipment list

The performance analysis should include sensitivities of results to parameters such as CO₂ purity, conversion efficiencies, pressure, temperature, and flow changes.

Integration opportunities within the CO₂C process and to an existing power generation plant or industrial plant should be examined where appropriate.

2.4. Economics

Global economic assumptions for NETL's cost analyses are listed in the Cost Estimation Methodology QGESS. [7] Deviations should be explicitly justified on a case-by-case basis. If the CO₂C technology is designed to replace some or all of an existing product source, financial considerations typical of the existing market should be examined for applicability.

Typically, cost estimates are not available for the year that an advanced technology is expected to be installed. Dollar values from similar capital cost estimates can be adjusted to the desired year using indices. Two such indices are the gross domestic product chain-type price index (GDPCTPI) (available on-line at no cost) and the chemical engineering plant cost index (CEPCI) (available for a subscription fee). [19, 20]

2.4.1. Product Demand/Price

If the CO₂C technology generates a product that is currently commercially available, the current price for that product and the size of the market are critical to establishing the economic viability of the CO₂C process. If the product generated by the CO₂C process is significantly more expensive than the current commercial process, it's unlikely to gain market share. If the market is currently small, then implementing the CO₂C technology on the CO₂ output from a single power plant could saturate the market and eliminate future growth for the technology. Literature searches can supply information on current and projected markets. Requests for information from current vendors and discussions with current production facilities can provide data on current markets as well as projections into the future.

2.4.2. Capital Costs

For equipment and sub-system items that can be identified in an NETL baseline study, use the baseline study cost and scaling guidelines to estimate the bare erected cost (BEC). [8, 10] For equipment that is not included in an NETL baseline study, attempt to identify an analog from an NETL study or from a literature source and scale it using the guidelines or recommendations from an engineering textbook or handbook. [17, 16] Discuss the rationale for this decision in the TEA costing section.

If no other sources are available, prepare a list of the major pieces of equipment in the sub-system, including process parameters, physical size, and materials of construction, and perform a bottom-up estimate of the sub-system. Commercial cost estimation software is available, but some of those tools may under- or over-estimate capital costs. The outputs should be scrutinized and adjusted as necessary, particularly when it comes to material and labor cost adders to install equipment (e.g., BEC-level costs).

For a case where the technology is TRL 1–2, and a Phase 1 capital cost estimate provides insufficient results, an incremental cost increase approach could be applied. In this instance, the incremental cost increase above the current sale price of the product, based on incorporating costs for the technologically mature aspects of the CO₂C technology, could be calculated. For example, a CO₂C technology needs 500 psi pure CO₂, which means capture and compression must be added to the reference plant (Fossil Energy Baseline Case B12B) for the amount of CO₂

that goes into the product (but at a lower pressure than that assumed in Fossil Energy Baseline Case B12B). The incremental cost, per unit CO₂ used, adds \$X/ton to the current market price of the product. The percentage increase of the current price provides insight into the viability of the CO₂C technology. In this example, the bounds are capture and compression, but they could extend to mature aspects of the CO₂C technology—for example, if the technology needs H₂ as a reactant, and will apply a novel reactor configuration; the reactor may be difficult to cost, but generating H₂ using a natural gas reformer is a mature technology, so it could be included as an incremental cost to represent the impact of adding H₂ generation to the CO₂C product price.

If initial capital values are based on equipment and material costs only, installation and labor costs can be estimated as a percentage of those costs, but in practice can vary greatly. The Fossil Energy Baseline Revision 4 capital costs or other NETL studies as well as engineering design textbooks can be used as guides if actual costs are not available. [8, 17] Turn-key cost estimates include installation and start-up costs but still may require additional costs for tie-ins to other plant processes.

Cost uncertainty can be addressed by performing sensitivity analyses on individual equipment items or the overall process costs. The product cost sensitivity to individual equipment item costs can identify areas where R&D will have the greatest impact. The extent of analog cost scaling employed for the CO₂C technology should be factored into determination of the scope of sensitivity studies considered.

Process and project contingencies are included in estimates to account for anticipated but unspecified costs due to a lack of complete project definition and engineering. Contingencies are added because experience has shown that such costs are likely, and expected, to be incurred even though they cannot be explicitly determined at the time the estimate is prepared as explained in the guidelines for power study TEAs. [4] AACE provides recommendations on the amount of contingency to be added for various classes of estimates and the expected level of accuracy based on the level of engineering available for the estimate. [9] Distinctions should be made between 1st-of-a-kind (FOAK) and NOAK estimates when calculations are based on actual plant estimates. [13] The contingency values used in NETL studies are included in the Cost Estimation Methodology QGESS. [7]

Owner's costs are added to capital cost estimates to account for typical additional costs beyond those based on the equipment and process design (e.g., start-up costs, land, financing cost, feasibility studies, road and railway construction, permitting costs). AACE and the Electric Power Research Institute (EPRI) provide guidance for determining these costs. [21, 22] The Cost Estimation Methodology QGESS lists the values typically assumed in NETL studies, which are specific to fossil-fueled power plants. [7] Land requirements for novel technologies are more difficult to estimate, and the buffer between the plant proper and the fence line will vary based on plant size, type, and location. For example, 1) a 650 MW-gross pulverized coal power plant may require 30 acres for the plant proper, and a 0.25 mile buffer to the fence line [8]; 2) a 2×1 F-Class natural gas combined cycle plant may require 10 acres for the plant proper, and a 0.15 mile buffer to the fence line [8]; and 3) a 100 MW battery of aeroderivative natural gas simple cycle units may require 4.5 acres for the plant proper, and a 250 ft buffer to the fence line. The plant proper can be scaled linearly from reference plants based on plant size, but the buffer to the fence line is static, based on regulations and permit requirements.

If a CO₂C technology is designed to be retrofitted to an existing plant, then a retrofit difficulty factor should be applied to the capital costs to represent the cost premium, addressing minor differences in equipment specifications, layout, duct routing, and items where additional complexity is likely to be encountered as well as labor productivity losses associated with working on an existing operating plant site in potentially highly congested areas, and with modifications and tie-in to existing equipment and/or systems. These factors range from 1.00 to 1.30 applied to the greenfield equivalent installation labor costs for the retrofit. These factors are discussed in more depth in the QGESS: Carbon Capture Retrofit Studies. [12]

The sum of the equipment, material, installation labor, and contingency costs is called the total plant cost (TPC). The TPC plus the owner's costs and other financial costs are called the total overnight cost (TOC). These are explained in more detail in the Cost Estimation Methodology QGESS and the baseline reports. [8, 7]

2.4.3. Operating and Maintenance Costs

O&M costs should be based on values for similar processes and should be itemized where possible. The baseline reports, other NETL studies, literature searches, and vendor information can provide starting points for estimates.

Fixed O&M costs include labor and supervision for both normal O&M. While the number of operators, supervisors, and maintenance workers is usually constant for a given process, the labor rate and burden can vary widely between locations. Typical values used in NETL studies are included in the baseline reports. [8] The assumed number of operators may be higher if the CO₂C technology has more operational complexity or challenges than the technology presented in the source process. These values are often difficult to define for novel technologies and can be subject to sensitivity analyses if further clarity is desired.

Maintenance material costs are included in the variable O&M and are typically assumed to be based on the ratio of a reference case maintenance material cost to TPC. The ratio should be adjusted as appropriate and is dependent on the nature of the CO₂C technology. For example, maintenance material costs for a membrane-based system may be higher than that for a solvent-based system if the entire membrane should be replaced periodically.

Variable O&M also includes consumables and waste disposal charges. Typical prices used in NETL studies are included in the baseline reports. [8] Literature searches or vendor information may provide values for new or specialized consumables. Some consumable prices may need to be increased if transportation to or from the CO₂C site is an issue. If there are saleable byproducts, then they should be included as a credit in the variable O&M.

Purchased municipal/local utilities (power, steam, water [process or cooling]) should be included as additional consumables within the variable O&M costs. If required power is to be purchased, a value for grid price should be determined by program management on a case-by-case basis.

Fuel costs are another variable O&M cost component, but they are treated as separate line items in most NETL studies with each fuel value presented individually. Coal and natural gas prices should follow the fuel cost guidelines. [23]

If some of the TEA focus is on renewables, identify the capacity factor needed to produce a competitive product (selling price) when using low cost/free electricity. If needed, include capital/O&M cost for energy storage such that high-capacity factors can be achieved.

If the end use is permanent storage of the CO₂, include capital/O&M costs for monitoring potential releases of CO₂ from the storage medium, if appropriate based on the CO₂C technology and product market best practices.

In typical NETL retrofit studies, the operation of the existing plant is assumed to continue with minimal disruptions, and the existing plant O&M costs are ignored in the financial calculations. [13] If this is not the case due to expected issues with integration of the new technology into the existing plant, then those values should also be included in the TEA calculations.

2.4.4. Sensitivities

The sensitivity of the CO₂C product cost to parameters like capital cost, O&M cost, fuel cost, utilities costs, capacity factor, and other variables with (potentially) a high degree of uncertainty can identify the most impactful areas for further R&D. For example, the sensitivity analysis might show that reducing capital cost is necessary to produce an economically competitive product; or that the cost of a co-reactant is prohibitive, and its use must be minimized or eliminated. Technology specific parameters like reactor cost, reactor efficiency, catalyst cost, catalyst capacity, and catalyst lifecycle should also be considered since these variables often exhibit a high degree of uncertainty for novel technologies. Presentation of the uncertainty results in a tornado diagram format is often useful to illustrate relative impacts.

2.5. Reporting Metrics

Critical challenges identified in the CO₂C focus area include the cost-effective use of CO₂ as a feedstock for chemical synthesis, or its integration into pre-existing products. The efficiency (reaction conversion and the amount of CO₂ sequestered in a product) and energy use (the amount of energy required to utilize CO₂ in existing products) of these CO₂C processes also represent a critical challenge.

In order to meet these challenges, metrics are developed to enable comparison of such technologies and CO₂C processes. In the not-too-distant past, authors and organizations have described using “sustainability metrics” to guide decision-making in the process industries for the goals of environmental protection, economic prosperity, and social benefit. [24, 25, 26, 27]

A *metric*, in the context here, is defined as “a standard of measurement.” [28]

Various aspects of RD&D projects, also thought of as processes or technologies, can have standards of measurement developed and defined for them. The purpose of this section is to present some standards of measurement.

The two most common groups of metrics are those dealing with economics (costs and values of inputs, outputs, and processes, including capital and operating costs) and performance (mass conversion, energy efficiency, and, generally speaking, energy and mass balance-derived parameters).

Economic and performance metrics are needed to be able to compare and/or screen varied RD&D projects and technologies from different perspectives or points of view. It is important to have available as wide a set of metrics as possible, because, at this stage of development, there are usually gaps in the information available; these vary from project to project and technology to technology, such that not every metric can be evaluated for each. Having a diverse set of

metrics allows for RD&D projects and technologies to be compared by at least one or more of these metric methods, and for meaningful comparisons to be drawn.

Depending on the priorities of an organization or the goals of RD&D programs, different metrics may be weighted differently in their application. Thus, some metrics may be considered more important than others.

Such assessments and comparisons assist in decision-making for allocating limited funds and resources to the most promising processes or technologies, according to the metrics that are judged to be the most important.

Metrics are designed to provide technology developers with targets for future development of their technology/process, not to eliminate projects from the portfolio. NETL developed a comprehensive set of metrics to enable meaningful comparison of different CO₂C technologies. The metrics that are applicable are detailed here.

2.5.1. Case Study

Sample calculations are included for each metric based on the screening TEA of a microwave-assisted carbon conversion catalyst technology. This process is comprised of a microwave-assisted dry reforming of methane (MW-DRM) reactor to produce syngas followed by a methanol plant. The BFD and select performance and cost results are included here for reference.

Certain metrics require the selection of a reference plant that uses a traditional technology analogous to the novel CO₂C technology. For the sample calculations of these metrics, a separate methanol-producing process is considered, with an autothermal reformer replacing the MW-DRM reactor. This reference plant maintains a methanol production rate equivalent to the MW-DRM reactor system.

Metrics that consider the CO₂C technology as an add-on to a fossil-fueled power plant require the selection of a reference plant that is a CO₂ emitter. For the sample calculations of these metrics, an appropriate case is chosen from NETL's Fossil Energy Baseline report. [8]

Exhibit 2-2: BFD for MW-DRM + MeOH Process

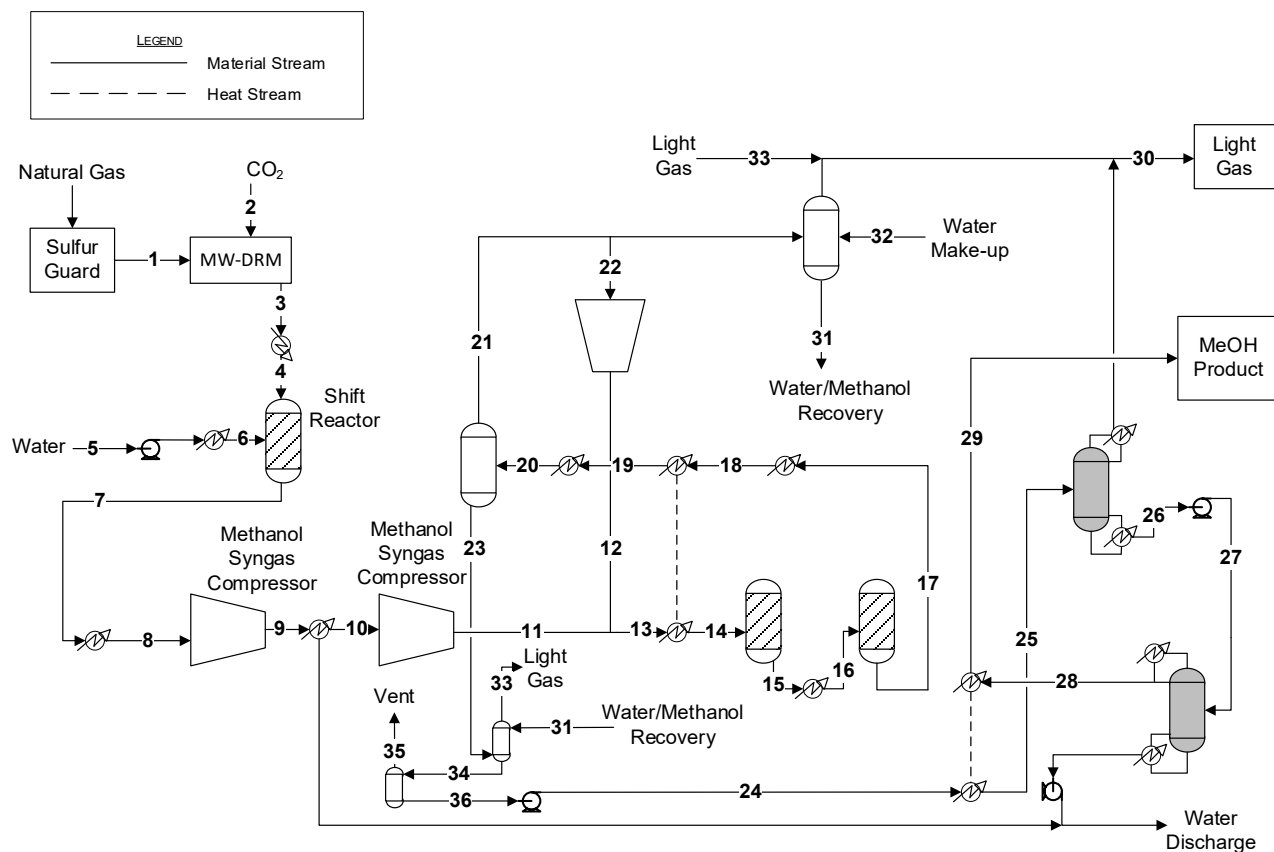


Exhibit 2-3: Performance and Cost Summary for MW-DRM + MeOH Process

Performance Summary		
	Value	Relevant Streams
MeOH Production Rate, Gallons/Year	60,999,868	29
CO ₂ In, Tonne/Year	203,845	1, 2
CO ₂ Out, Tonne/Year	141,500	30, 35
CO ₂ Utilized, Tonne/Year	62,345	1, 2, 30, 35
MW-DRM Reactor Efficiency, kW/(Tonne CO ₂ /Hour)	3,024	N/A
Cost Summary		
Levelized Cost of MeOH, \$/Gallon	1.86	
Capacity Factor	85%	
First Year Variable O&M Cost, \$/Year (100% CF, excl. power)	8,473,324	
Annual Purchased Power, \$/Year (100% CF)	53,368,636	
First Year Feedstock Cost, \$/Year (100% CF)	20,236,208	
First Year Fixed O&M Cost, \$/Year	7,145,223	
Total Plant Cost, \$/Year	230,426,191	
Total Overnight Cost, \$/Year	308,846,914	

2.5.2. Performance Metrics

CO₂ Conversion Efficiency

CO₂C efficiency is defined as the amount of CO₂ utilized (CO₂ in – CO₂ out) on a mass basis per unit amount of CO₂ fed to the CO₂C process. This represents the simplest way of thinking about a CO₂C metric. It is a dimensionless ratio and is preferably expressed as a percentage. The higher the percentage, the more efficient the CO₂C process.

For a continuous flow process, this metric is expressed as the flow rate of CO₂ into the process minus the flow rate of CO₂ leaving the process divided by the flow rate of CO₂ into the process.

$$\begin{aligned} \text{CO}_2 \text{ Conversion Efficiency (\%)} &= \frac{\text{Tonne CO}_2 \text{ Utilized}}{\text{Tonne CO}_2 \text{ Fed to Process}} \times 100 \\ &= \frac{(\text{Tonne/Year CO}_2 \text{ In} - \text{Tonne/Year CO}_2 \text{ Out})}{\text{Tonne/Year CO}_2 \text{ In}} \times 100 \end{aligned}$$

Example: A MW-DRM reactor system is fed 203,845 tonnes per year of CO₂. Total CO₂ emitted and captured from this process adds up to 141,500 tonnes per year of CO₂.

$$\begin{aligned} \text{CO}_2 \text{ Converted (Tonne/Year)} &= 203,845 \text{ Tonne/Year CO}_2 - 141,500 \text{ Tonne/Year CO}_2 \\ &= 62,345 \text{ Tonne/Year CO}_2 \end{aligned}$$

$$\text{CO}_2 \text{ Conversion Efficiency (\%)} = \frac{62,345 \text{ Tonne/Year CO}_2}{203,845 \text{ Tonne/Year CO}_2} \times 100 = 30.6\%$$

CO₂ Conversion Potential

CO₂C potential is the amount of CO₂ that would be utilized (CO₂ in – CO₂ out) on a mass basis to meet the desired product's market demand, relative to the amount of CO₂ emitted from a user-specified reference CO₂ emitter or plant. This metric represents the potential of a CO₂C technology to reduce emissions at a fossil-fired power plant by producing a marketable product. It is a dimensionless ratio and can be expressed as a percentage. The geographic basis for the product market demand should be specified, e.g., the United States, North America, or the World. Also, the CO₂ emission stream reference basis should be defined, since the metric is dependent on this reference, e.g., a single power plant emission, total U.S. coal-fired power plants emissions, etc. Furthermore, the reference CO₂ basis can be further defined as the CO₂ emitted, or as the CO₂ captured in a carbon capture scenario. In the latter definition, the CO₂ captured represents the CO₂ available to the CO₂C process.

$$\begin{aligned} \text{CO}_2 \text{ Conversion Potential (\%)} &= \frac{\text{Tonne/Year CO}_2 \text{ Utilized to Meet Market Demand}}{\text{Tonne/Year CO}_2 \text{ Available from Reference Plant}} \times 100 \end{aligned}$$

Example: The market demand of methanol in North America was 8,394,000 tons (7,615,000 tonnes) in 2020 [29]. If a MW-DRM system produced enough methanol to meet this demand, CO₂ utilized would be 2,599,000 tonnes per year. A supercritical pulverized coal power plant

without capture (Fossil Energy Baseline Case B12A) emits 3,763,000 tonnes per year of CO₂ as the reference basis.

$$CO_2 \text{ Conversion Potential (\%)} = \frac{2,599,000 \text{ Tonne/Year } CO_2}{3,763,000 \text{ Tonne/Year } CO_2} \times 100 = 69.1\%$$

If the entire U.S. fleet of pulverized coal power plants were considered in place of the individual plant, the total CO₂ emissions would be 956,652,000 tonnes per year.

$$CO_2 \text{ Conversion Potential (\%)} = \frac{2,599,000 \text{ Tonne/Year } CO_2}{956,652,000 \text{ Tonne/Year } CO_2} \times 100 = 0.3\%$$

CO₂ Conversion Intensity

CO₂C intensity is the amount of CO₂ utilized (CO₂ in – CO₂ out) on a mass basis per unit amount of the desired product. This metric is a dimensionless ratio and should be expressed as a percentage. It may be thought of as a ‘mass version’ of the chemical reaction stoichiometry (which is done on a mole basis).

$$CO_2 \text{ Conversion Intensity (\%)} = \frac{\text{Tonne } CO_2 \text{ Utilized}}{\text{Tonne Product Produced}} \times 100$$

$$= \frac{(\text{Tonne/Year } CO_2 \text{ In} - \text{Tonne/Year } CO_2 \text{ Out})}{\text{Tonne/Year Product Produced}} \times 100$$

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO₂. The system produces 61 M gallons per year of methanol which is equivalent to 182,650 tonnes per year.

$$CO_2 \text{ Conversion Intensity (\%)} = \frac{62,345 \text{ Tonne/Year } CO_2}{182,650 \text{ Tonne/Year MeOH}} \times 100 = 34.1\%$$

CO₂ Integration Reaction Rate

The CO₂ integration reaction rate is the molar rate of CO₂ utilized per unit of reactor volume. The molar rate can be on any time basis, such as lb-mol/hr, and the reactor volume can be on any convenient volume basis, such as gallons. In this case, the metric units would be lb-mol/(gal·hr). This metric is a measure of the reactor volume required in the technology’s current state of development to meet the desired production rate.

$$CO_2 \text{ Integration Reaction Rate} = \frac{\text{lbmol/hr } CO_2 \text{ Utilized}}{\text{Gallons of Reactor Volume Required for Reaction}}$$

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO₂ (356.3 lb-mol per hour). Assume the volume of the MW reactor is 1,000 gallons (a purely hypothetical value).

$$CO_2 \text{ Integration Reaction Rate} = \frac{356.3 \text{ lbmol } CO_2/\text{hr}}{1,000 \text{ Gallons}} = 0.3563 \text{ lbmol}/(\text{gal} * \text{hour})$$

CO₂ Energy Conversion

The CO₂ energy conversion metric is defined as the net amount of energy required per unit amount of CO₂ utilized (mass basis). It is a measure of the energy efficiency of the technology or process to utilize CO₂. The units for the energy conversion metric are kW/(tonne CO₂ per hour).

$$CO_2 \text{ Energy Conversion (kW/(Tonne CO}_2\text{/hr))} = \frac{\text{kW Energy Required}}{\text{Tonne/Hour CO}_2\text{ Utilized}}$$

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO₂. The normalized microwave efficiency of the reactor is 3,024 kW per tonne per hour of reactor inlet CO₂. The system is fed 203,845 tonnes per year of CO₂.

$$\begin{aligned} CO_2 \text{ Energy Utilization (kW/(Tonne CO}_2\text{/Hour))} \\ &= \frac{3,024 \text{ kW/(Tonne CO}_2\text{/Hour)} \times 203,845 \text{ Tonne CO}_2\text{/Year}}{62,345 \text{ Tonne CO}_2\text{/Year}} \\ &= 9,887 \text{ kW/(Tonne CO}_2\text{/Hour)} \end{aligned}$$

Notional Energy Penalty

The notional energy penalty (NEP) metric uses the enthalpy change of the CO₂ conversion reaction as a marker to identify energy intensive technologies. The equation describing this metric is shown here:

$$NEP \equiv \Delta H_{rxn}^o - Q_{NZCS}$$

where ΔH_{rxn}^o is the enthalpy change of the reaction to convert CO₂ to the desired product, and Q_{NZCS} is the heat available from near-zero carbon energy sources. Q_{NZCS} could include solar radiation, waste thermal energy, renewable electricity, hydrogen, or other sources of energy. The metrics report proposes an NEP limit of 100 kJ/mol CO₂ converted as a benchmark, which is based on the energy required to produce carboxylic acid products. Processes with higher energy requirements cannot compete unless renewable energy is available to offset the energy needed. NEP is not a rigorous analysis of energy requirements, only providing a basic assessment of the ideal energy involved in the production path. Evaluating other product pathway energetics and completing a comparison will be necessary to give context to the 100 kJ/mol CO₂ converted baseline.

2.5.3. Cost Metrics

Global economic assumptions for NETL's cost analyses are listed in the Cost Estimation Methodology QGESS. [7] Deviations may be explicitly justified on a case-by-case basis.

For many cost metrics include the annualization of the capital costs of a CO₂C project by performing a discounted cash flow (DCF) analysis or multiplying the total capital costs by a capital charge factor. [7] When a new project is being financed and constructed, a finance structure is developed specific to the market conditions and the ownership risks. The cost analyses performed by NETL for baseline studies are for both near-term construction of commercial technologies, with 2023 as the on-line year, as well as for advanced technologies, which are typically assumed to be commercial 15 years or more into the future. For the purpose of comparing technologies in the Fossil Energy Baseline Revision 4 [8], the same finance structure was applied to all scenarios, and only real dollars were used. All technologies are

considered to be commercial ready—there are neither applicable tax subsidies nor risks associated with first-of-a-kind construction or immature design. Therefore, the structure chosen for developing the financing for major power projects is that of a large, financially stable, investor-owned utility (IOU) or merchant plant. CO₂C projects may need to use different financial assumptions based on research and market conditions and government incentives, but the equations presented in the Cost Estimation Methodology QGESS are still applicable. [7]

Required Purchase Price

The first program metric is the required purchase price of CO₂ (RPP). This metric represents the price at which the CO₂C technology can afford to purchase CO₂ from the CO₂ producer and remain cost competitive with the current state of the art production method. The total cost to the CO₂C plant includes transportation costs, investment costs, and physical requirements such as purity, pressure, and temperature. The metric is dependent on the price of the product made from CO₂, the capital charges involved with producing the product, which include return on investment for the CO₂C plant, the fixed operational costs, and the variable costs aside from the fluctuating cost of CO₂. The formula to calculate RPP is shown here:

$$\left\{ \begin{array}{c} \text{Required Purchase} \\ \text{Price of CO}_2 \end{array} \right\} \equiv \left\{ \begin{array}{c} \text{Product} \\ \text{Sale Price} \end{array} \right\} - \left\{ \begin{array}{c} \text{Capital} \\ \text{Charge} \end{array} \right\} - \left\{ \begin{array}{c} \text{Fixed} \\ \text{Costs} \end{array} \right\} - \left\{ \begin{array}{c} \text{Variable Costs} \\ \text{Excluding CO}_2 \end{array} \right\}$$

To create a meaningful result for RPP, the cost information used must be reliable and well-described, which may be difficult for low-TRL technologies whose system embodiments have not been sufficiently defined. Furthermore, financial parameters such as market price and conditions as well as delivery cost inclusion versus freight on board pricing should be well-established. Since the price of capturing carbon is essential for CO₂C to be economically feasible, the RPP must meet the cost of capture of CO₂.

Example: A MW-DRM reactor system produces 61 M gallons per year of methanol at a breakeven levelized cost of \$1.86 per gallon when CO₂ is assumed to be free. The MW-DRM reactor system takes in 224,623 tons per year of CO₂. The total cost excluding CO₂ can then be calculated.

$$\left\{ \begin{array}{c} \text{Total Cost} \\ \text{Excluding CO}_2 \end{array} \right\} = \left\{ \begin{array}{c} \text{Capital} \\ \text{Charge} \end{array} \right\} + \left\{ \begin{array}{c} \text{Fixed} \\ \text{Costs} \end{array} \right\} + \left\{ \begin{array}{c} \text{Variable Costs} \\ \text{Excluding CO}_2 \end{array} \right\}$$

$$= \frac{61 \text{ M Gallons/Year} \times \$1.86/\text{Gallon}}{224,623 \text{ Ton CO}_2/\text{Year}} = \$505.11/\text{Ton CO}_2$$

The market price for methanol is assumed to be \$488 per tonne (\$1.46 per gallon) which generates a revenue of \$92,120,554 per year when applied to the production rate. Product sale price can then be calculated.

$$\left\{ \begin{array}{c} \text{Product} \\ \text{Sale Price} \end{array} \right\} = \frac{\$92,120,554/\text{Year}}{224,623 \text{ Ton CO}_2/\text{Year}} = \$410.11/\text{Ton CO}_2$$

The required purchase price of CO₂ can then be calculated.

$$\left\{ \begin{array}{c} \text{Required Purchase} \\ \text{Price of CO}_2 \end{array} \right\} \equiv \left\{ \begin{array}{c} \text{Product} \\ \text{Sale Price} \end{array} \right\} - \left\{ \begin{array}{c} \text{Capital} \\ \text{Charge} \end{array} \right\} - \left\{ \begin{array}{c} \text{Fixed} \\ \text{Costs} \end{array} \right\} - \left\{ \begin{array}{c} \text{Variable Costs} \\ \text{Excluding CO}_2 \end{array} \right\}$$

$$= \$410.11/\text{Ton CO}_2 - \$505.11/\text{Ton CO}_2 = -\$95.00/\text{Ton CO}_2$$

This result suggests that a credit of \$95 per ton of CO₂ must be applied for this process to be cost competitive with the current state of the art production methods.

Levelized Cost of Product

The breakeven levelized cost of product (LCOP) can be calculated by summing the annualized total capital, the annual fixed O&M costs, the annual variable O&M costs (including all feedstocks, fuels, and consumables) at an assumed capacity factor and dividing by the annual product generated. When the product is electricity, this value is the levelized cost of electricity and the product unit is MWh per year. [7] For a retrofit project the annual values can be defined as the incremental difference between the after-retrofit values minus the existing plant values. [12] The LCOP is calculated as

$$LCOP = \frac{(TVOM + TFOM + TOC * TASC/TOC * FCF)}{\text{Product Units per Year}}$$

where:

- LCOP – levelized cost of product, \$/unit
- TVOM – total annual variable O&M, \$/yr including fuel costs if any
- TFOM – total annual fixed O&M, \$/yr
- TOC – total overnight cost, \$
- TASC/TOC –total overnight cost to total as-spent cost basis multiplier
- FCF – fixed charge factor, fraction

Example: The LCOP for a MW-DRM system is desired at a capacity factor of 100 percent. Cost estimates for a MW-DRM reactor system show a first year variable O&M cost of \$8,473,324 per year excluding power. First year feedstock cost was determined to be \$20,236,208 per year. Annual purchased power cost is \$53,368,636.

$$TVOM = \$8,473,324/\text{Year} + \$20,236,208/\text{Year} + \$53,368,636/\text{Year}$$

$$= \$82,078,168/\text{Year}$$

First year fixed O&M cost was determined to be \$7,145,223 per year at a capacity factor of 85 percent.

$$TFOM = \$7,145,223/\text{Year} \times (100/85) = \$8,406,145/\text{Year}$$

Total overnight cost was determined to be \$308,847,000 at a capacity factor of 85 percent. The TASC/TOC multiplier and fixed charge factors are 1.07 and 0.0586, respectively.

$TOC * TASC/TOC * FCF = \$308,847,000 \times 1.07 \times 0.0586 \times (100/85) = \$22,782,735/\text{Year}$

Assuming methanol production of 60,999,868 gallons per year, LCOP is calculated as follows.

$$LCOP = \frac{\$82,078,168/\text{Year} + \$8,406,145/\text{Year} + \$22,782,735/\text{Year}}{60,999,868 \text{ Gallons MeOH}/\text{Year}}$$

$$= \$1.86/\text{Gallon MeOH}$$

Product Marketability

The product marketability metric is the cost to make a unit amount of the desired product relative to the market value of that product. This metric is a dimensionless ratio and should be expressed as a percentage.

$$\text{Product Marketability (\%)} = \frac{\$ \text{ Cost to Make a Tonne of Desired Product}}{\$ \text{ per tonne Market Value of Desired Product}} \times 100$$

Example: A MW-DRM reactor system produces methanol at a breakeven levelized cost of \$1.86 per gallon. The market price of methanol is assumed to be \$488 per tonne (\$1.46 per gallon).

$$\text{Product Marketability (\%)} = \frac{\$1.86/\text{Gallon MeOH}}{\$1.46/\text{Gallon MeOH}} \times 100 = 127\%$$

Cost per Tonne CO₂ Utilized

The cost per tonne of CO₂ utilized metric is the sum of annualized capital and operating costs of the CO₂C process relative to the tonnes of CO₂ utilized. The costs of the process are to include infrastructure, raw materials, processing, byproduct disposal, and utilities costs, as well as any other costs. The units of this metric are \$ per tonne of CO₂. This metric is dependent on the maturity or stage of development of the technology or process, and whether the costs are known or can be reasonably estimated. A new CO₂C pathway must be more cost effective than the process it aims to replace.

$$\begin{aligned} \text{Cost per Tonne CO}_2 \text{ Utilized (\$/Tonne)} \\ = \frac{\sum \text{Annualized Capital and Operation Costs (\$/Year)}}{\text{Tonne/Year CO}_2 \text{ Utilized}} \end{aligned}$$

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO₂. The total plant cost is \$230,426,191 per year.

$$\text{Cost per Tonne CO}_2 \text{ Utilized (\$/Tonne)} = \frac{\$230,426,191/\text{Year}}{62,345 \text{ Tonne CO}_2/\text{Year}} = \$3,696/\text{Tonne CO}_2$$

Incremental Cost Reduction

If there is a traditional process for making the desired product that the new CO₂C process is replacing, then the incremental cost reduction metric is the incremental reduction in cost by the new CO₂C process over the traditional process. This metric builds on the previous Cost per Ton CO₂ Utilized metric by including materials costs for feedstock, catalysts, and others not included in equipment and operating costs. The unit of this metric is U.S. dollar per tonne of product. This metric needs to have a positive value to show there is a cost saving to be had in replacing the traditional process.

$$\begin{aligned} \text{Incremental Cost Reduction (\$/Tonne)} \\ = ((\$ \text{ Cost to Make a Tonne of Product by Traditional Process}) - \\ (\$ \text{ Cost to Make a Tonne of Product by New Process})) \end{aligned}$$

Example: A MW-DRM reactor system produces methanol at a breakeven levelized cost of \$1.86 per gallon (\$621 per tonne). A separate methanol-producing system uses an autothermal reformer in place of the MW-DRM reactor to produce syngas. This traditional plant produces methanol at a breakeven levelized cost of \$0.89 per gallon (\$297 per tonne). Methanol is produced at equivalent rates in both plants.

$$\begin{aligned} \text{Incremental Cost Reduction (\$/Tonne)} &= \$297/\text{Tonne MeOH} - \$621/\text{Tonne MeOH} \\ &= -\$324/\text{Tonne MeOH} \end{aligned}$$

This result suggests a cost increase of \$324 per tonne of methanol for the MW-DRM reactor system.

2.5.4. Emissions Metrics

CO₂ Emission Metric

CO₂ emission metric is the CO₂ emissions of the new CO₂C pathway versus the CO₂ emissions of the traditional pathway. The new process must reduce the overall CO₂ emissions.

$$\text{CO}_2 \text{ Emission Metric} = \frac{\text{Tonne CO}_2 \text{ Emission in New Process}}{\text{Tonne CO}_2 \text{ Existing or Traditional Process}}$$

Example: A MW-DRM reactor system emits 141,500 net tonnes per year of CO₂. A separate methanol-producing system uses an autothermal reformer in place of the MW-DRM reactor to produce syngas. This traditional process emits 30,444 tonnes per year of CO₂.

$$\text{CO}_2 \text{ Emission Metric} = \frac{141,500 \text{ Tonne CO}_2/\text{Year}}{30,444 \text{ Tonne CO}_2/\text{Year}} = 4.65$$

This result suggests that the MW-DRM reactor system does not reduce overall CO₂ emissions.

CO₂ Emissions Reduction

If there is a traditional process for making the desired product that the new CO₂C process is replacing, then the CO₂ emissions reduction metric is the amount of CO₂ emissions reduction per unit amount of product in the new process, relative to that in the traditional process. This metric is a dimensionless ratio and should be expressed as a percentage. The greater the value, the greater is the CO₂ emissions reduction.

$$\begin{aligned} \text{CO}_2 \text{ Emission Reduction (\%)} &= \frac{\text{Tonne CO}_2 \text{ Emission Reduction}}{\text{Tonne CO}_2 \text{ Existing Emissions}} \times 100 \\ &= \frac{(\text{Tonne/Year CO}_2 \text{ Emitted in Existing Process} - \text{Tonne/Year CO}_2 \text{ Emitted in New Process})}{\text{Tonne/Year CO}_2 \text{ Emitted in Existing Process}} \times 100 \end{aligned}$$

Example: A MW-DRM reactor system emits 141,500 net tonnes per year of CO₂. A separate methanol-producing system uses an autothermal reformer in place of the MW-DRM reactor to produce syngas. This traditional process emits 30,444 tonnes per year of CO₂.

$$\begin{aligned}
 & \text{CO}_2 \text{ Emission Reduction (\%)} \\
 &= \frac{30,444 \text{ Tonne CO}_2/\text{Year} - 141,500 \text{ Tonne CO}_2/\text{Year}}{30,444 \text{ Tonne CO}_2/\text{Year}} \times 100 = -365\%
 \end{aligned}$$

This result suggests that the MW-DRM reactor system demonstrates an increase in CO₂ emissions of 365%.

CO₂ Avoided Potential

If there is a traditional process for making the desired product that the new CO₂C process is replacing, then the CO₂ avoided potential metric is the amount of CO₂ avoided by the new process over the traditional process and assumed to offset CO₂ emissions from a user-specified reference CO₂ emitter or plant. This metric is a dimensionless ratio and should be expressed as a percentage. Put another way, the CO₂ avoided potential is the percentage of the reference plant CO₂ emissions that the new process would avoid producing, when considering the CO₂C process and reference CO₂ emitter within the same envelope.

$$\begin{aligned}
 & \text{CO}_2 \text{ Avoided Potential (\%)} \\
 &= \frac{\text{Tonne/Year of CO}_2 \text{ Avoided to Meet Market Demand}}{\text{Tonne/Year of CO}_2 \text{ Emitted from Reference Plant}} \times 100 \\
 &= \frac{(\text{Tonne/Year CO}_2 \text{ Emitted from Existing Process} - \text{Tonne/Year CO}_2 \text{ Emitted from New Process})}{\text{Tonne/Year CO}_2 \text{ Emitted from Reference Plant}} \times 100
 \end{aligned}$$

Example: The market demand of methanol in North America was 8,394,000 tons (7,615,000 tonnes) in 2020 [29]. If a MW-DRM system produced enough methanol to meet this demand, net CO₂ emitted would be 5,899,000 tonnes per year. A separate methanol-producing system uses an autothermal reformer in place of the MW-DRM reactor to produce syngas. If this system produced enough methanol to meet demand, CO₂ emitted would be 1,269,000 tonnes per year. A supercritical pulverized coal power plant without capture (Fossil Energy Baseline Case B12A) emits 3,763,000 tonnes per year of CO₂ as the reference basis.

$$\begin{aligned}
 & \text{CO}_2 \text{ Avoided Potential (\%)} \\
 &= \frac{1,269,000 \text{ Tonne CO}_2/\text{Year} - 5,899,000 \text{ Tonne CO}_2/\text{Year}}{3,763,000 \text{ Tonne CO}_2/\text{Year}} \times 100 \\
 &= -123\%
 \end{aligned}$$

This result suggests that the MW-DRM reactor system will not avoid CO₂ emissions if used in place of the traditional process.

2.5.5. Market Metrics

Product Supply-Demand

The product supply-demand metric is the percentage of the desired product market that can be satisfied with the new process or technology, taking into consideration feedstock or catalyst availability, or other limitations. This metric is a dimensionless ratio that should be expressed as

a percentage. The geographic basis for the product market demand should be specified, e.g., the United States, North America, or the World.

$$\begin{aligned} \text{Product Supply-Demand Metric (\%)} \\ = \frac{\text{Tonne/Year of Product that Can Be Produced}}{\text{Tonne/Year of Market Demand for that Product}} \times 100 \end{aligned}$$

Example: Assume that a MW-DRM reactor system utilizes the CO₂ emissions of a supercritical pulverized coal plant with 90% capture (Fossil Energy Baseline Case B12B). The amount of CO₂ emitted is 480,897 tonnes per year, limiting the potential methanol production of the MW-DRM reactor system to 430,895 tonnes per year. The market demand of methanol in North America was 8,394,000 tons (7,615,000 tonnes) in 2020 [29].

$$\text{Product Supply-Demand Metric (\%)} = \frac{430,895 \text{ Tonne MeOH/Year}}{7,615,000 \text{ Tonne MeOH/Year}} \times 100 = 5.66\%$$

Cumulative Market Value

Cumulative market value (CMV) demonstrates the available market for functionally equivalent products (FEPs) produced by the process. FEPs are products created by CO₂C technologies that are functionally identical to products currently in production that have the same end-use (e.g., methanol for chemical use versus methanol for liquid fuels). CMV is calculated using the following formula:

$$CMV = \sum_{i=1}^p w_{USD}(i) f_{AMP}(i) v_{FEP}(i)$$

where $w_{USD}(i)$ is the revenue from total global sales of functionally equivalent product i in U.S. dollars, f_{AMP} is the assumed market penetration value, and v_{FEP} is the global annual production of functionally equivalent products. The f_{amp} factor represents an opportunity for sensitivity studies where the potential global market value can be assessed at 10 percent penetration, 90 percent penetration, or any reasonable value. Judgment of an acceptable market penetration factor value will be contingent on the projected cost of product calculated. For example, if a technology projects a cost of product that is twice the current standard production method product cost, or current market purchase price, a case could be made that no market penetration will occur.

Example: The global production of methanol was 106,598,000 tons (96,704,000 tonnes) in 2020 [29]. At a market price of \$488 per tonne, this corresponds to a yearly revenue of \$47,192,000,000 [30]. Assume a market penetration value of 20 percent.

$$CMV = w_{USD} * f_{AMP} * v_{FEP} = \$47,192,000,000 * 0.20 * 96,704,000 = \$9.1273 \times 10^{17}$$

2.5.6. Other Metrics

Relative Safety and Environmental Benefits

The relative safety and environmental benefits metric is a composite assessment of the raw materials and processing conditions, including any environmental benefits, of the new process

relative to those of any existing process for the same product. The metric assessment is either improved, no change, or reduced.

The relative safety ranking uses the NFPA Standard 704 “fire diamond” category hazard values, which range from 0 to 4, with 0 meaning no hazard and 4 meaning severe hazard. [31] The NFPA categories are those of health, flammability, and instability/reactivity. There is also a special notice category for oxidizing materials, materials having unusual reactivity with water, and simple asphyxiants. [32]

An improved relative safety assessment could be based on reduced reactor temperature and/or pressure, elimination of a hazardous feedstock or catalyst, etc.

Examples of improved environmental benefits assessments include the elimination of a petroleum-based feedstock, elimination of a toxic by-product, reduction in raw water consumption, or reduction in air pollutant emissions.

Other Strategic Benefits

Externalities reflect qualitative policy judgments established by DOE management but are not quantified in the carbon capture and conversion RD&D program, but they should be addressed qualitatively in any TEA and may be quantifiable for specific projects. [5]

Externalities include

- National Security
- Economic Growth
- Competitiveness
- Infrastructure
- Environmental
- Long-Term Storage Potential
- Long-Term Carbon Neutrality/Negativity Potential

2.6. Quality Control

Quality assurance/quality control procedures should be carried out at the discretion of, and under the guidance of, the QGESS user’s policies to ensure accurate cost and performance estimates are reported.

2.7. Issues to Address Qualitatively

All studies should include a qualitative examination of the impact of the changes in design and operating assumptions for the CO₂C technology on the TEA results.

2.7.1. Potential Concerns, Advantages, and Disadvantages

Contaminants in flue gas from a boiler may negatively impact the capture system and result in contaminants in the CO₂ stream fed to a CO₂C technology. Control and/or mitigation

requirements for these constituents should be examined and included in the performance and cost estimates as needed, and as data supports.

For retrofit technologies, the impact on the performance of other plant systems and products should be examined to see if changes or upgrades would be needed to handle the CO₂C technology design and meet existing regulations for modified systems.

Cooling water constraints in specific areas can determine if a dry or hybrid cooling system needs to be installed.

2.7.2. Commercialization Plan (Feed Availability, Product Market)

A commercialization plan for the CO₂C technology and new products should be developed. If the process generates existing commercial products, or requires feedstock of existing commercial products, the impact on the current and future markets should be examined. Additionally, the availability of compatible feeds should be determined, as feeds meeting the specified purity requirements may be prohibitively expensive or unavailable on a commercial scale.

2.7.3. Flexibility Issues

With the increasing demand for flexibility in operating formerly baseload plants at lower capacity factors and off-design conditions, any retrofit TEA study should include an examination of the impact of operating at part load or load following conditions. This includes the impact on any CO₂C technology where the CO₂ product stream from a power generation plant is the feedstock for the CO₂C technology. Questions to be answered are as follows:

What are the impacts/concerns of the CO₂ feedstock being supplied at lower flow rates with potential changes in purity or conditions?

What are the impacts/concerns of partial load operation of a plant supplying CO₂ on the conversion system operation overall?

What are the impacts/concerns of partial load operation on reagent or catalyst degradation?

Studies are providing indications of how flexible operation of coal-fired CO₂ capture plants could be realized. [33] These could provide information on the impact flexible operation imparts on the CO₂ product from capture systems that need to be addressed in the design of CO₂C processes.

Variable consumables and waste disposal flows result in variable O&M costs for the capture system. The effect of partial load operation on CO₂C reagent and catalyst degradation is not well characterized in the open literature and could cause more variability in O&M costs than expected. [34]

2.7.4. Safety/Environmental Impact

Safety and environmental impacts, including considerations related to environmental justice, of the CO₂C process shall be examined to the best extent possible. Additional equipment or capital may be required to mitigate any potential hazards.

3. Summary

CO₂C technologies cover a wide range of processes and end products. Because it's not possible to address every eventuality in a single document, the most important aspects of the TEA are the integrated process definition and documentation of all assumptions, data sources, and calculations. NETL's QGESS and Fossil Energy Baseline report are referenced in this document, and they provide guidance for many of the situations that will be encountered when assessing CO₂C technologies. To the extent possible, the QGESS and baseline report should form the basis of the analyses. When situations arise that aren't covered by the QGESS and baseline reports, estimations and scaling based on similar processes can be used as methods to fill in missing information if the data sources are referenced, and the calculations are documented.

The metrics presented in this quality guideline were developed for use with CO₂C through chemical conversion processes. The goal is to provide normalized metrics (unit per ton of CO₂ consumed) that allow comparison of dissimilar technologies. Other types of metrics could be proposed, such as those used for chemistry: yield, atom economy, and reaction mass efficiency, and should be defined and cited by the technology developer if relevant to their technology. [26]

These metrics give simple standards of measurement to gauge performance and economics of RD&D projects relative to their contemporary counterparts, and between interdisciplinary CO₂C fields. This provides useful tools for decision-makers for benchmarking performance, tracking improvement, evaluating products and processes, and developing strategies for prioritizing and allocating limited resources, such as RD&D funding. [25]

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