BASIS FOR TECHNO-ECONOMIC ANALYSIS

CARBON UTILIZATION PROCUREMENT GRANTS

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Disclaimer

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LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
AACE	AACE International
abs	Absolute
BEC	Bare erected cost
BIL	Bipartisan Infrastructure Law
Btu	British thermal unit
CH4	Methane
CF	Capacity factor
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2C	CO_2 conversion
DOE	Department of Energy
Eng'g CM H.O. & Fee	Engineering construction management home office and fees
EPAct	Energy Policy Act
EPCC	Engineering, procurement, and construction cost
FCF	Fixed charge factor
FECM	Office of Fossil Energy and Carbon Management
FEP	Functionally equivalent product
FOA	Funding Opportunity Announcement
ft^3	Cubic feet
gal	Gallon
GHG	Greenhouse gas
gpm	Gallons per minute
H_2	Hydrogen
H_2O	Water
HCl	Hydrochloric acid
Hg	Mercury
hr, h	Hour
kg	Kilogram
kg_{mol}	Kilogram-mole
kJ	Kilojoule
kW, kWe	Kilowatt electric
lb	Pound
lb_{mol}	Pound-mole
LCA	Life cycle analysis
LCOP	Levelized cost of product
M	Million
m^3	Cubic meter
MEB	Material and energy balance
MeOH	Methanol
min	Minute
mol	Mole
MPa	Megapascal
MW-DRM	Microwave-assisted dry reforming of methane
MWh	Megawatt hour
N/A	Not applicable
NEP	Notional energy penalty
NETL	National Energy Technology Laboratory
NOx	Nitrous oxides
O&M	Operation and maintenance
O-H	Overhead
O_2	Oxygen
PFD	Process flow diagram
psia	Pounds per square inch absolute
QGESS	Quality Guidelines for Energy System Studies
RD&D	Research, development, and deployment
RPP	Required purchase price of CO_2
SO_2	Sulfur dioxide
TASC	Total as-spent cost
TEA	Techno-economic analysis
TFOM	Total annual fixed O&M
TOC	Total overnight cost
tonne	Metric ton
TPC	Total plant cost
TVOM	Total annual variable O&M
UPGrants	Utilization Procurement Grants
U.S.	United States of America
V-L	Vapor-liquid
yr, y	Year

Glossary of Terms

Bare Erected Cost	The sum of material, labor, and equipment costs. Bare erected cost comprises the cost of process equipment, on-site facilities, and infrastructure that support the facility and the direct and indirect labor required for its construction.
Capital Cost	The cost of fixed, one-time expenses for the development of a facility such as the purchase of equipment, land, infrastructure, and the labor required for its construction.
Carbon Conversion	The transformation of carbon oxides into value-added products such as biofuels, chemicals, and building materials
Carbon Conversion Metric	A standard of measurement that enables comparison between carbon utilization/conversion technologies typically describing a fundamental aspect of the technology (i.e., economics, performance, market information, or emissions)
Carbon Conversion Technology	A technology that converts carbon oxides into a value-added product
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
Carbon Oxide Source	An existing carbon oxide-producing process or naturally occurring source that can serve as a feedstock provider for a 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
Eligible Entity	Eligible entities are defined as states[a], units of local governments, and public utilities or agencies
Emitter	A process or unit operation that emits greenhouse gases
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

[a] "State means any state of the United States, the District of Columbia, the Commonwealth of Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, the Commonwealth of the Northern Mariana Islands, and any agency or instrumentality thereof exclusive of local governments." [18]

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)
Material and Energy Balance	The calculation of all mass and energy flows to and from a process or between unit operations based on the conservation of mass and energy
Operating & 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; operation 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 Model	A model of a process developed utilizing available tools/software that generates useful performance information about said process including energy and mass balances and equipment performance based on design assumptions
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
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 Flow Diagram	Diagram of a process including major unit operations and streams, including feedstocks and products that are within the scope of the system.
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
Reporting Metric	A standard of measurement reported as a result of a techno-economic analysis
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 techno-economic analysis 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
Technology Readiness Level	A system of ranking technology maturity, from conception to full deployment, developed by the National Aeronautics and Space Administration
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
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 and raw material price)
Vendor	A carbon conversion product manufacturer from whom eligible entities will procure and use commercial and industrial products derived from anthropogenic carbon oxides

1 Background

Submission of techno-economic analysis information by the vendor is voluntary; the information is not required but may be submitted in addition to the vendor's Life Cycle Analysis (LCA) submission. Submitting techno-economic analysis information (or opting not to) will have no impact on the critical review of the LCA.

The United States (U.S.) Department of Energy (DOE) National Energy Technology (NETL) has issued a Notice of Intent to issue a Funding Opportunity Announcement (FOA) on behalf of the Office of Fossil Energy and Carbon Management (FECM). The FOA is intended to be issued in the first quarter of Calendar Year 2023 and will be funded under authorization of the Bipartisan Infrastructure Law (BIL).

The BIL is an investment in infrastructure that will grow a more sustainable, resilient, and equitable economy through enhancing U.S. competitiveness, driving the creation of quality jobs, and ensuring stronger access to economic, environmental, and other benefits for disadvantaged communities. The BIL appropriates more than $62 billion to DOE to invest in U.S. manufacturing and workers; expand access to energy efficiency; deliver reliable, clean, and affordable power to more Americans; and deploy the technologies of tomorrow through clean energy demonstrations.

The Carbon Conversion Program, previously named the Carbon Utilization Program, intends to develop an opportunity funded via BIL Section 40302, which amended Section 969A of the Energy Policy Act of 2005 (EPAct 2005) (42 U.S.C. 16298a), to provide an incentive for the procurement and use of commercial and industrial products that are derived from anthropogenic carbon oxides. These demonstration grants will illustrate that carbon utilization/conversion products can replace incumbent products while significantly reducing greenhouse gas (GHG) emissions.

Anthropogenic carbon oxides are defined as human-created emissions of carbon dioxide (CO_2) or carbon monoxide (and mixtures thereof), including legacy emissions present within the atmosphere. Significant net reductions in GHG emissions must be demonstrated by a validated life cycle analysis (LCA) that demonstrates a 10 percent reduction in GHG emissions of the product derived from anthropogenic carbon oxides compared to an incumbent product. Eligible entities must engage with conforming product manufacturers (vendors) to procure carbon utilization/conversion-derived products. The vendor must submit information to the specified DOE website (https://www.netl.doe.gov/upgrants) to secure LCA validation that the product results in a significant net reduction (greater than 10 percent) in GHG emissions relative to incumbent commercial production technologies.

Concurrently, DOE requests that the vendor voluntarily provides information (both narrative and quantitative) on the performance and economics of the associated production facility, embodying the carbon utilization/conversion technology concept, used to manufacture the product(s). The vendor may provide to DOE the production cost and its basis, consistent with the quote provided to the eligible entity. The following document has been developed to provide guidance on the exact nature of the information that is being requested by DOE.

2 INTRODUCTION

The cost and performance of emerging and state-of-the-art carbon utilization/conversion technologies is evaluated through techno-economic analysis (TEA) methodology. To ensure that technologies can be evaluated fairly and can be compared across different conversion pathways and product markets, a transparent and consistent method for the relevant technical and economic evaluations is critical. Herein, this document applies the principles of and expands upon the NETL Quality Guidelines for Energy System Studies (QGESS) series of documents to be more relevant for vendors participating in the Utilization Procurement Grants (UPGrants) Program. The NETL documents relied upon for the development of this guidance include the following:

1. QGESS: Performing a Techno-Economic Analysis for Power Generation Plants [1]
2. QGESS: Performing a Techno-Economic Analysis for Carbon Conversion Technologies [2]
3. QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance [3]
4. QGESS: Capital Cost Scaling Methodology: Revision 4a Report [4]

The assumptions and calculations outlined here and in the referenced documents provide a common basis to develop cost and performance data for any applicable vendor technology. The guidelines presented here are not intended to be used to assess application materials, but to provide valuable information to DOE on cost and performance of various utilization/conversion technologies that are region specific.

Specifically, the basis for TEA as it relates to the UPGrants Program, may include the following:

1. A narrative description of the facility layout and configuration, accompanied by a process flow diagram (PFD) that identifies all major equipment
2. A detailed description of the critical process equipment, including novel technologies
3. Material and energy balance (MEB) diagrams and tables for the facility
4. Feedstock volumes (e.g., carbon oxide), utility demand (e.g., imported electric power and heat energy requirements), and assumed costs
5. Identification of products and byproducts (if applicable), anticipated and maximum production volumes for each, as well as the production cost and assumed sales prices
6. Economic analysis including facility capital and annual operation and maintenance (O&M) costs in a specified year-dollar
7. Applicable subsidies and/or incentives (e.g., tax credits)
8. Labor/staffing estimates for the facility (full-time equivalents) and anticipated wages and occupations
9. Identification of the number of temporary (e.g., construction) jobs, etc.

The information requested above may be accompanied by a pro forma income statement for the production facility/product(s) for one fiscal year. The pro forma income statement may include a baseline established from current/prior years (based on at least six months of continuous operation—the vendor should indicate if this is not available). The pro forma income statement may include estimates for costs of product sold, gross revenue, gross margin, and operating margin. All assumptions made in the generation of the income statement should be detailed.

The requested information should reflect the most recent complete calendar year at the time of submittal to the UPGrants Program. The carbon conversion/utilization process should use a minimum of six consecutive months of operational data from that calendar year in the calculation of its annual average operations.

If the anticipated annual production by the facility during the proposed grant term, consistent with the quote provided to the eligible entity, is less than the full design capacity of the facility, the vendor should provide the quantitative information requested above for the full design capacity of the facility.

If the facility used to manufacture the product under this DOE grant is at pre-commercial (e.g., pilot) scale or less mature, the information requested above should be provided for the notional future full-scale (commercial scale) embodiment of the production facility.

Additionally, to the extent data are available, market information should be provided for the products and byproducts that the vendor intends to produce. The analysis should include the size of the U.S. and global markets (in terms of both tonnage and revenue); anticipated growth; which countries are major producers, consumers, importers and exporters; and status of the U.S. in terms of production, consumption, imports and exports—identifying which countries the United States relies on for imports.

DOE shall provide a template to streamline the reporting of the information requested above. The remainder of the document provides additional detail on the items requested above.

3 Basis for Techno-economic Analysis

This section defines the TEA methodology as well as the requested cost and performance data to be developed using the outlined methodology. As part of the TEA, the vendor should provide a facility description, performance analysis, economic analysis, and market analysis. Further details on each aspect of the TEA are provided in the subsequent sub-sections. The information provided should include sufficient detail for DOE to determine the technical, economic, and environmental aspects of the resources required for commercial-scale operation of the facility.

The system boundaries for a TEA are smaller than that for an LCA and should encompass the entire carbon conversion/utilization facility from inputs to outputs. The system boundaries of a TEA do not consider the environmental impact of feedstock sources, manufacturing of process components, or the end-of-life disposition of products and waste streams. For example, a TEA defines the cost, pressure, temperature, and composition of an incoming carbon oxide stream, but LCA would be required to assess the environmental impact of how that carbon oxide stream was generated.

Rather than submitting information for multiple facilities, the vendor should choose a representative or averaged facility to serve as the basis for all cost and performance results submitted. All cost and performance results from the TEA should be reported in the accompanying reporting template provided by DOE.

3.1 Facility Description

This section details the information requested for the facility description. The information provided by the vendor in the facility description should include the following:

1. A narrative description of the model facility layout and configuration
2. A detailed description of the critical process equipment, including novel technologies
3. Identification of all products and by-products (if applicable)
4. Identification of all feeds (including feedstock sources), reagents, and consumables
5. Process parameters, assumptions, and primary reaction equations and pathways
6. A description of the current state of the technology
7. Identification of data gaps and uncertainties
8. A PFD with major equipment and streams
9. An itemized list providing major equipment and equipment specifications

The narrative description of the model facility layout and configuration should clearly define the carbon conversion/utilization technology including all feeds, reagents, products (and by-products), processes, and unit operations. Critical process equipment, including novel technologies, should be described in detail with equipment specifications, process parameters, assumptions, and other performance data pertinent to the carbon utilization/conversion technology. Feedstock sources, particularly carbon oxide feedstock sources, should be identified. The primary reaction equations as well as pathways should be provided and remaining data gaps should be identified. The current state of the technology should be described (e.g., pilot plant, demonstration plant, or commercial plant) and the estimated technology readiness level should be identified.

To accompany the narrative description, the vendor should provide a PFD around the scope of the carbon conversion/utilization facility including all major equipment and streams. All unit operations should be labeled, and streams should be numbered according to the stream numbers provided in the accompanying stream table (described further in Section 3.2).

The vendor should provide an itemized list of all critical process equipment included in the PFD. Equipment items may include but are not limited to, reactors, separation vessels, heat exchangers, pumps, and compressors. For each equipment item, the equipment list should provide a description, number of units, size information, and material specifications. An example of the equipment list as it appears in the accompanying template is included in Exhibit 3-1.

Exhibit 3-1. Equipment list

Equipment No.	Description	No. of units	Size	Material Specifications
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

3.2 Performance Analysis

This section details the information requested for the performance analysis. The information provided by the vendor in the performance analysis may include the following:

1. MEBs for the model facility
2. A stream table describing major streams as identified in the PFD
3. A table providing all auxiliary loads within the facility
4. A table providing plant emissions as compared to applicable regulatory limits
5. Sensitivity analyses on impactful parameters

3.2.1 Material and Energy Balances

MEBs around the model facility including all major equipment and streams should be provided by the vendor in the form of an MEB diagram. The diagram should include all flowrates, stream conditions (i.e., temperature, pressure, and enthalpy), heating and cooling duties, and electric power requirements. MEB calculations should be accurate and equilibria, physical properties, and thermodynamic properties should be calculated using rigorous models. For simple systems, a spreadsheet analysis may be possible. Examples of MEB diagrams are available in NETL's *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4* (the "Fossil Energy Baseline"). [5]

In addition to an MEB diagram, material balance tables should be provided for key components. Key components that should be included in material balance tables are carbon, water, and others, as appropriate. Carbon balances should include all carbon present in inlet and outlet streams and their difference should converge to zero. Water balances should identify the water demand, internal recycle, raw water withdrawal, process discharge, and raw water consumption for every applicable item. Examples of MEB tables as they appear in the accompanying template are available in Exhibit 3-2,
Exhibit 3-3, and
Exhibit 3-4.

3.2.2 Stream Table

The vendor should provide a stream table for the process with numbered streams that correspond to the PFD provided with the facility description (Section 3.1). For each major stream, the stream table should provide the following:

1. Vapor-liquid (V-L) mole fraction for every component
2. V-L molar flowrate (kg_{mol}/hr and lb_{mol}/hr)
3. V-L mass flowrate (kg/hr and lb/hr)
4. Solids mass flowrate (kg/hr and lb/hr)
5. Temperature (°C and °F)
6. Pressure (MPa absolute and psia)
7. Enthalpy (kJ/kg and Btu/lb)
8. Density (kg/m^3 and lb/ft^3)
9. V-L molecular weight

The accompanying template provides an example of how the stream table should be organized and which units should be used to report results. An example of the stream table as it appears in the accompanying template is available in Exhibit 3-5.

Exhibit 3-2. Carbon balance table

Carbon In			Carbon Out		
Inlet Description	kg/hr	lb/hr	Outlet Description	kg/hr	lb/hr
Carbon Inlet 1		0	Carbon Outlet 1		0
Carbon Inlet 2		0	Carbon Outlet 2		0
Carbon Inlet 3		0	Carbon Outlet 3		0
Total	**0**	**0**	**Total**	**0**	**0**
			Convergence Tolerance	0	0

Exhibit 3-3. Water balance table

Water Use	Water Demand		Internal Recycle		Raw Water Withdrawal		Process Water Discharge		Raw Water Consumption	
	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm
Water Use 1		0		0	0	0		0	0	0
Water Use 2		0		0	0	0		0	0	0
Water Use 3		0		0	0	0		0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Exhibit 3-4. Generic component balance table

Component In			Component Out		
Inlet Description	kg/hr	lb/hr	Outlet Description	kg/hr	lb/hr
Inlet 1		0	Outlet 1		0
Inlet 2		0	Outlet 2		0
Inlet 3		0	Outlet 3		0
Total	**0**	**0**	**Total**	**0**	**0**
			Convergence Tolerance	0	0

Exhibit 3-5. Stream table

	Stream Number									
Vapor-Liquid (V-L) Mole Fraction	1	2	3	4	5	6	7	8	9	10
CO2										
H2										
CO										
H2O										
CH4										
O2										
N2										
Total (Equals 1)	0	0	0	0	0	0	0	0	0	0
add or remove rows as necessary to include additional stream components or remove unused stream components. Identify any critical trace elements with their concentration.										
V-L Flowrate (kgmole/hr)										
V-L Flowrate (kg/hr)										
Solids Flowrate (kg/hr)										
Temperature (°C)										
Pressure (MPa, abs)										
Enthalpy (kJ/kg)										
Density (kg/m^3)										
V-L Molecular Weight										
V-L Flowrate (lbmole/hr)	0	0	0	0	0	0	0	0	0	0
V-L Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0
Solids Flowrate (lb/hr)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	32	32	32	32	32	32	32	32	32	32
Pressure (psia)	0	0	0	0	0	0	0	0	0	0
Enthalpy (Btu/lb)	0	0	0	0	0	0	0	0	0	0
Density (lb/ft^3)	0	0	0	0	0	0	0	0	0	0

3.2.3 Auxiliary Load Table

The vendor should provide a table with all itemized auxiliary loads, and the total auxiliary load, for the model facility. Auxiliary loads may include but are not limited to, reactors, compressors, pumps, turbines, fans, and miscellaneous plant loads. An example of the auxiliary load table as it appears in the accompanying template is available in Exhibit 3-6.

Exhibit 3-6. Auxiliary load table

Item	Auxiliary Load, kWe
Auxiliary Load 1	
Auxiliary Load 2	
Auxiliary Load 3	
Auxiliary Load 4	
Auxiliary Load 5	
Auxiliary Load 6	
Auxiliary Load 7	
Auxiliary Load 8	
Auxiliary Load 9	
Auxiliary Load 10	
Power Generated	0
Total Auxiliaries	0
Net Auxiliaries	0

3.2.4 Emissions Table

The vendor should provide a table with the flowrates of all regulated air emissions from the model facility. These results should be presented alongside regulatory limits, with the regulatory limit standard identified, for each component emissions. The accompanying template provides an example of how the emissions table should be organized. An example of the emissions table as it appears in the accompanying template is available in Exhibit 3-7.

Exhibit 3-7. Emissions table

Component	Tonne/Yr	kg Emitted/kg Product	Location-Specific Regulations / Regulatory Limit Standard
SO2			
NOx			
Particulate			
Hg			
HCl			
CO2			

3.2.5 Sensitivity Analyses

The vendor may provide sensitivity analyses on impactful parameters, such as capital cost, O&M cost, fuel cost, utilities cost, or capacity factor. Technology specific parameters like reactor cost, reactor efficiency, catalyst cost, catalyst capacity, and catalyst life cycle may also be considered. For example, a sensitivity that shows a significant cost reduction across the sensitivity range may be useful to describe the economic potential of the carbon conversion/utilization technology. The accompanying template provides direction of where to include sensitivity analyses, if completed.

3.3 Economic Analysis

This section details the information requested for the economic analysis. The information provided by the vendor in the economic analysis should include the following:

1. Economic assumptions used to generate cost estimates
2. Capital cost estimates for the model facility including itemized capital costs for major equipment
3. O&M cost estimates for the facility
4. Production cost estimates for all products that the vendor intends to produce
5. Pro-forma income statement

These economic analysis requirements help demonstrate the viability of a given technology, based on a set of market conditions for the utility power generation market. Capital and O&M cost estimates should be itemized as shown in the Fossil Energy Baseline and should use the same dollar basis found in an appropriate reference case.

3.3.1 Economic Assumptions

The vendor should provide all economic assumptions used to generate cost information, including global economic assumptions, finance structures, and return on equity. Global economic assumptions for NETL's cost analyses are listed in Exhibit 3-8. Global economic assumptions do not need to equal those listed; however, the vendor should provide information for each listed parameter. An example of the economic assumptions table as it appears in the accompanying template is available in Exhibit 3-9. This table should be expanded as necessary to include economic assumptions that are not already listed.

Exhibit 3-8. Global economic assumptions for NETL studies

Parameter	Value
Taxes	
Income Tax Rates	21% federal, 6% state (Effective tax rate 25.74%)
Capital Depreciation	20 years, 150% declining balance
Investment Tax Credit	0%
Tax Holiday	0 years
Contracting and Financing Terms	
Contracting Strategy	Engineering Procurement Construction Management (owner assumes project risks for performance, schedule, and cost)
Type of Debt Financing	Non-recourse (collateral that secures debt is limited to the real assets of the project)
Repayment Term of Debt	Equal to operational period in formula method
Grace Period on Debt Repayment	0 years
Debt Reserve Fund	None
Analysis Periods	
Capital Expenditure Period	Natural gas plants: 3 years Coal plants: 5 years
Operational Period	30 years
Economic Analysis Period	33 or 35 years (capital expenditure period plus operational period)
Treatment of Capital Costs	
Capital Cost Escalation During Capital Expenditure Period	0% real (3% nominal)
Distribution of Total Overnight Capital over the Capital Expenditure (before escalation)	3-year period: 10%, 60%, 30% 5-year period: 10%, 30%, 25%, 20%, 15%
Working Capital	Zero for all parameters
% of Total Overnight Capital that is Depreciated	100% (actual amounts are likely lower, and do not influence results significantly)
Escalation of Operating Costs and Revenues	
Escalation of Cost of Electricity (revenue), O&M Costs	0% real (3% nominal)
Fuel Costs	See QGESS Fuel Prices for Selected Feedstocks in NETL Studies [7]

Exhibit 3-9. Economic assumptions table

Assumption	Units	Value
Capacity Factor	%	
Fixed Charge Rate	Decimal	
Total as-spent cost (TASC) / total overnight cost (TOC)	Decimal	
Year Cost Basis		
Feedstock Price	$/kg	
CO_2 Price	$/ton	
Purchased Electricity Price	$/MWh	
Makeup Water Price	$/1,000 gal	

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 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). Vendors should report the finance structure used to generate cost estimates. Further information regarding finance structures is available in NETL's *QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance.* [3]

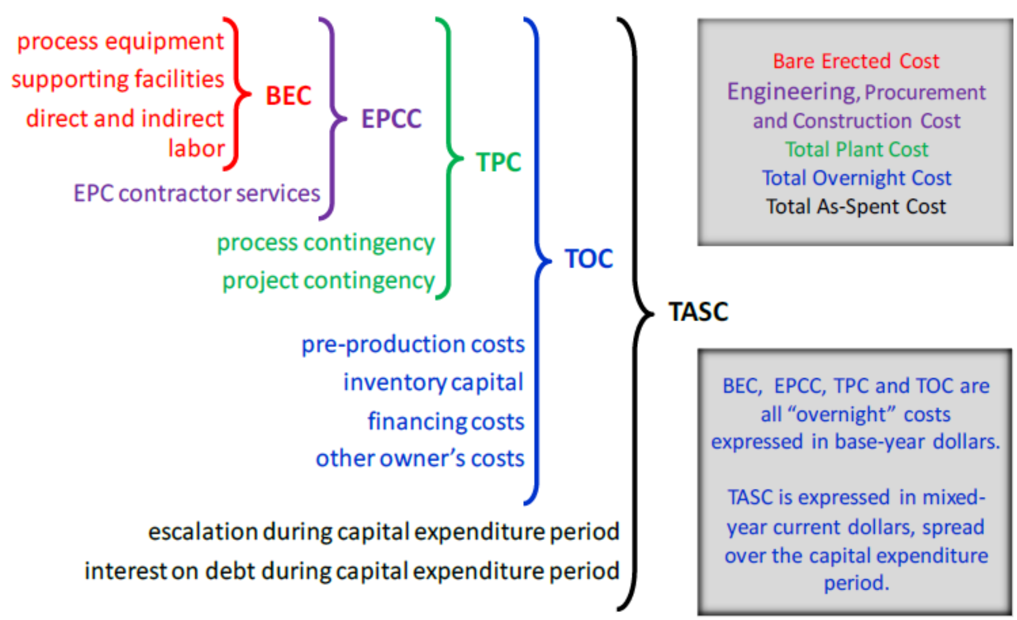
3.3.2 Capital Costs

The vendor should provide capital cost estimates for the model facility. As illustrated in Exhibit 3-10, there are five levels of capital costs that should be considered during cost development. The levels are defined as the following:

1. Bare Erected Cost (BEC) comprises the cost of process equipment, on-site facilities and infrastructure that support the plant (e.g., shops, offices, labs, road), and the direct and indirect labor required for its construction and/or installation.
2. Engineering, Procurement, and Construction Cost (EPCC) comprises the BEC plus the cost of services provided by the EPC contractor. The EPC services include detailed design, contractor permitting (i.e., those permits that individual contractors must obtain to perform their scopes of work, as opposed to project permitting, which is not included here), and project/construction management costs.
3. Total Plant Cost (TPC) comprises the EPCC cost plus project and process contingencies.
4. Total Overnight Capital (TOC) comprises the TPC plus all other "overnight" costs, including owner's costs. TOC is an overnight cost, expressed in base-year dollars and as such does not include escalation during construction or construction financing costs.
5. Total As-Spent Capital (TASC) comprises the sum of all capital expenditures as they are incurred during the capital expenditure period for construction including their escalation. TASC also includes interest during construction, comprised of interest on debt and a return on equity. TASC is expressed in mixed, current-year dollars over the capital expenditure period.

BEC, EPCC, TPC, and TOC are overnight costs and are expressed in base-year dollars. The base year is the year in which all technology costs are expressed for the comparison of technologies from a standard starting point. TASC is expressed in mixed, current-year dollars over the entire capital expenditure period, which is assumed in most NETL studies to last five years for coal plants and three years for natural gas plants. If one wants to portray all plants in real dollars, the base year typically is used for the real dollar year. The vendor should use the same dollar basis found in an appropriate reference case to develop capital costs. Further information on capital cost development is available in NETL's *QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance* and NETL's *QGESS: Capital Cost Scaling Methodology: Revision 4a Report*. [3] [4]

Exhibit 3-10. Capital cost levels and their elements



The vendor should provide an itemized table of capital cost estimates for all pieces of equipment that are included in the equipment list (described further in Section 3.1). Equipment should be itemized as shown in the Fossil Energy Baseline. For each piece of equipment, the vendor should report the equipment cost, material cost, labor cost (both direct and indirect), BEC, engineering construction management home office and fees (Eng'g CM H.O. & Fee), process and project contingencies, and the contribution to TPC. TOC and TASC should be calculated for the entire facility as described in NETL's *QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance*. [3] Capital cost uncertainties for equipment and systems that do not yet exist may be established using AACE International (AACE) guideline uncertainties at the class level appropriate to the analysis. [7] The capital cost table as it appears in the accompanying template is available in Exhibit 3-11.

The vendor should provide a table of owner's cost estimates for the model facility. Owner's cost is itemized into pre-production costs, inventory capital, and other owner's costs. TOC is the resulting sum of these owner's costs and is multiplied by the TASC multiplier to obtain TASC. The owner's cost table as it appears in the accompanying template is available in Exhibit 3-12.

Exhibit 3-11. Capital cost table

Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/kg
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
Total		0	0	0	0	0	0	0	0	0	0

Exhibit 3-12. Owner's cost table

Owner's Costs		
Description	$/1,000	$/gal
Pre-Production Costs		
6 Months All Labor		
1 Month Maintenance Materials		
1 Month Non-fuel Consumables		
1 Month Waste Disposal		
25% of 1 Months Fuel Cost at 100% Capacity Factor (CF)		
2% of Total Plant Cost (TPC)		
Total:	**0**	**0**
Inventory Capital		
60 Day Supply of Fuel and Consumables at 100% CF		
0.5% of TPC		
Total:	**0**	**0**
Other Costs		
Initial Cost for Catalyst and Chemicals		
Land		
Other Owner's Costs		
Financing Costs		
Total Overnight Costs (TOC):	**0**	**0**
TASC Multiplier		
Total As-Spent Cost (TASC):	**0**	**0**

3.3.3 Operation & Maintenance Costs

The vendor should provide O&M cost estimates for the model facility including fixed O&M costs (including labor costs), variable O&M costs, and feedstock costs.

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. The assumed number of operators may be higher if the carbon utilization/conversion 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. In most cases, the advanced technology may not have the ability to reduce the operating labor category by reducing the reference base case number of operators. However, changes to the number of operators due to known operational complexity of the advanced technology is encouraged and allows for a more transparent understanding of the advanced technology's operational challenges or advantages by TEA reviewers.

Variable O&M costs include maintenance material costs (assumed in NETL studies to be based on the ratio of a reference case maintenance material cost to TPC), consumables, and waste disposal charges. Typical prices for these items used in NETL studies are included in the Fossil Energy Baseline. The vendor may provide values for new or specialized consumables. Some consumable prices may need to be increased if transportation to or from the facility 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 the assumed grid price in the appropriate region should be provided by the vendor.

Feedstock and fuel costs are another variable O&M cost component, but they are treated as separate line items in most NETL studies with each feedstock or fuel value presented individually. The vendor should provide a value for all assumed feedstock and fuel prices in the appropriate region.

If the end use is permanent storage of the CO_2, include capital/O&M costs for monitoring potential releases of CO_2 from the storage medium, if appropriate based on the carbon utilization/conversion 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. 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.

The vendor should provide an itemized list of O&M cost estimates. O&M costs should be itemized as shown in the Fossil Energy Baseline. The O&M cost table as it appears in the accompanying template is available in Exhibit 3-13.

Exhibit 3-13. O&M cost table

O&M Labor							
Operating Labor			Units			Operating Labor Requirements per Shift	
Operating Labor Rate (base):			$/hour			Skilled Operator:	
Operating Labor Burden:			% of base			Operator:	
Labor O-H Charge Rate:			% of labor			Foreman:	
						Lab Techs, etc.:	
						Total:	**0**
Fixed Operating Costs							
						Annual Cost	
						$	$/kg product
Annual Operating Labor							
Maintenance Labor							
Administrative & Support Labor							
Property Taxes and Insurance							
Total:						**0**	**0**
Variable Operating Costs							
						$	$/kg product
Maintenance Material:							
Consumables							
		Initial Fill	Per Day	Per Unit	Initial Fill Cost		
Water					0	0	
Electricity					0	0	
Additional Consumables					0	0	
Subtotal:						**0**	**0**
Feedstock Cost							
Carbon Dioxide					0	0	
Additional Feedstocks					0	0	
Total:						**0**	**0**

3.3.4 Production Costs

The vendor should provide estimated production costs for all productions intended to be sold. This information should be provided in the form of levelized costs of product (LCOP) for each product sold. The 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. For a retrofit project the annual values can be defined as the incremental difference between the after-retrofit values minus the existing plant values. The LCOP is calculated as

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

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

The vendor should provide values for both the total LCOP and LCOP components (i.e., capital, fixed O&M, variable O&M [excluding purchased electricity], feedstock, and purchased electricity). The LCOP table as it appears in the accompanying template is available in Exhibit 3-14.

Exhibit 3-14. LCOP table

LCOP Component	LCOP	
Capital	$/kg	
Fixed O&M	$/kg	
Variable O&M (excl. purchased electricity)	$/kg	
Feedstock	$/kg	
Purchased Electricity	$/kg	
Total	**$/kg**	**0**

3.3.5 Pro-Forma Income Statement

The information requested above should be accompanied by a pro forma income statement for the production facility/product(s) for each fiscal year of the proposed grant term. The pro forma income statement should include a baseline established from current/prior years (based on at least six months of continuous operation—the vendor should indicate if this is not available). The pro forma income statement should include estimates for costs of product sold, gross revenue, gross margin, and operating margin. All assumptions made in the generation of the income statement should be detailed.

3.4 Market Analysis

This section details the information requested for the market analysis. The information provided by the vendor in the market analysis should include the following:

1. Market information for each product (and by-product) including market demand, market share, regional spot prices, and national prices
2. Market limitations such as resource availability and supply chain considerations
3. Incentives such as subsidies and tax credits
4. Comparison between market information and economic results such as anticipated and maximum production volumes, production costs, and assumed sales prices
5. Regionality considerations for all market information

For each product, the vendor should provide market information including market demand, market share, regional spot prices, and national prices. This information should reflect the most recent complete calendar year at the time of submittal to the UPGrants Program. Any market limitations such as resource availability and supply chain considerations should be identified. Any incentives including subsidies and tax credits applicable to a sold product may be discussed.

The market information table as it appears in the accompanying template is available in Exhibit 3-15.

Exhibit 3-15. Market information table

	Units	Product 1	Product 2	Product 3	Notes
Market Demand	U.S. Tons				
Market Share	$				
Spot Prices	$/kg				
Region 1					
Region 2					
Region 3					
Region 4					
National Price	$/kg				

The market information provided should then be compared to the economic results from the TEA in order to make a business case for the carbon conversion/utilization technology. Anticipated and maximum production volumes for the model facility may be reported and compared to the market demand and market size. Production costs and assumed sales prices may be compared to the regional spot prices and national prices for all products. The impact of plant location on the economics of the model facility may also be discussed.

3.5 Carbon Conversion Metrics

This section details the information and calculations requested for carbon conversion metrics. The vendor should provide a table with the results of the calculated carbon conversion metrics for the model facility. Typically, only select carbon conversion metrics are calculated, as the utility of certain metrics depends on the characteristics of the evaluated technology. All carbon conversion metrics should be calculated to the extent practical and applicable.

Critical challenges identified in developing carbon utilization/conversion technologies include the cost-effective use of CO_2 and other carbon oxides as a feedstock for chemical synthesis, or its integration into pre-existing products. The efficiency (reaction conversion and the amount of carbon oxides sequestered in a product) and energy use (the amount of energy required to utilize carbon oxides in existing products) of these processes also represent a critical challenge.

In order to meet these challenges, metrics are developed to enable comparison of such carbon utilization/conversion technologies. 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. [8] [9] [10] [11]

A metric, in the context here, is defined as "a standard of measurement." [12]

Various aspects of carbon utilization/conversion 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 research, development, and deployment (RD&D) projects and technologies from different perspectives or points of view. 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 characteristics of a carbon utilization/conversion technology, 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 carbon utilization/conversion technologies.

The metrics that are applicable are detailed here. Although these metrics can be applied to any carbon oxide, the definitions and sample calculations for each metric provided herein consider CO_2 as the carbon oxide of interest.

3.5.1 Case Study

Sample calculations are included for each metric based on a screening TEA of a microwave-assisted carbon conversion catalyst technology. This process comprises a microwave-assisted dry reforming of methane (MW-DRM) reactor to produce syngas followed by a methanol (MeOH) plant. A simple PFD and select performance and cost results are included in Exhibit 3-16 and Exhibit 3-17 for reference.

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

Metrics that consider the carbon utilization/conversion technology as an add-on to a fossil-fueled power plant require the selection of a reference plant that is a CO_2 emitter. For the sample calculations of these metrics, an appropriate case is chosen from the Fossil Energy Baseline. [6]

Exhibit 3-16. PFD for MW-DRM + MeOH synthesis process

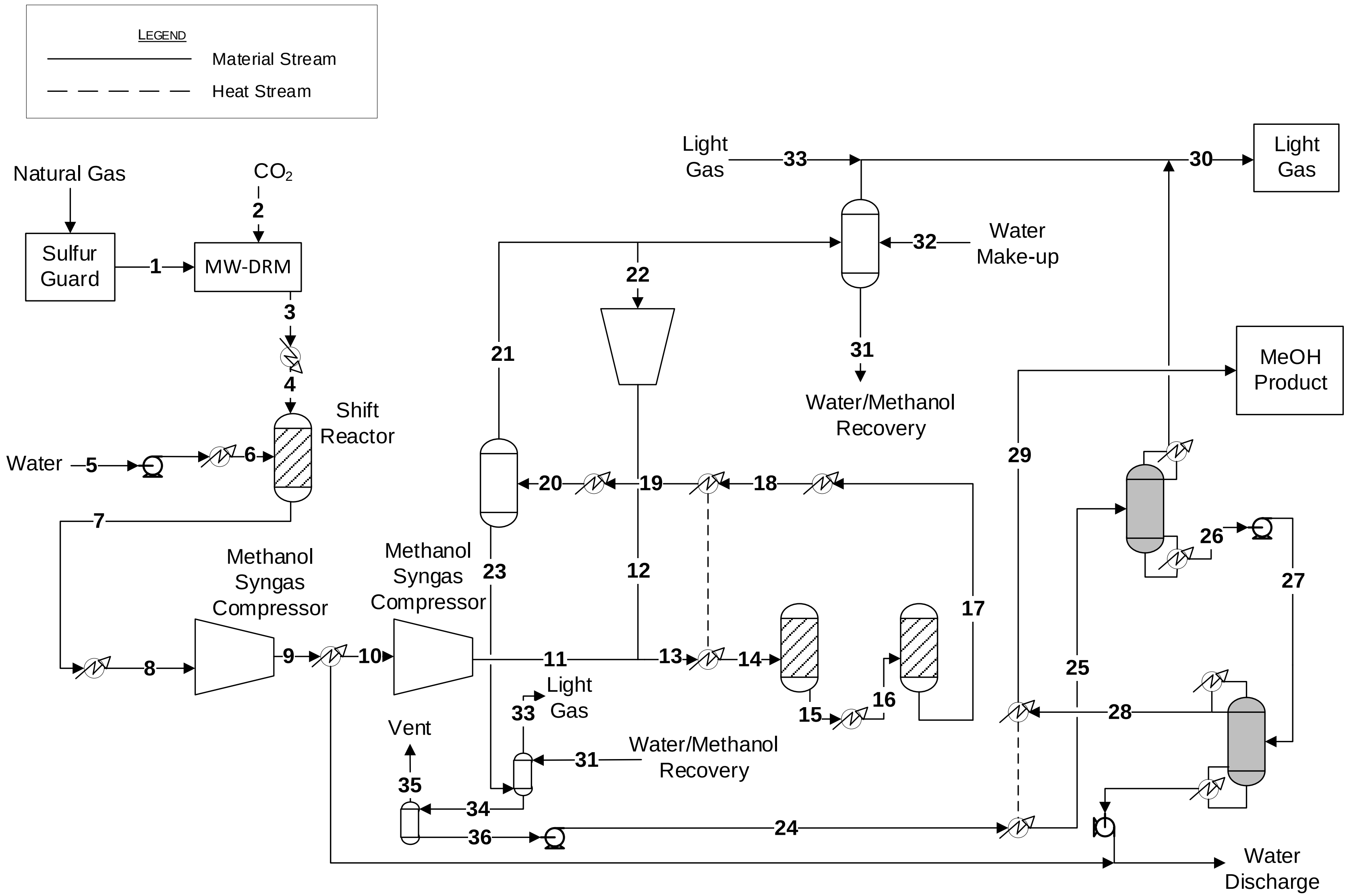


Exhibit 3-17. Performance and cost summary for MW-DRM + MeOH synthesis process

Performance Summary		
	Value	Relevant Streams
MeOH Production Rate, gal/yr	60,999,868	29
CO_2 In, tonne/yr	203,845	1, 2
CO_2 Out, tonne/yr	141,500	30, 35
CO_2 Utilized, tonne/yr	62,345	1, 2, 30, 35
MW-DRM Reactor Efficiency, kW/(tonne CO_2/hr)	3,024	N/A
Cost Summary		
Levelized Cost of MeOH, $/gal	1.86	
Capacity Factor	85%	
First Year Variable O&M Cost, $/yr (100% CF, excl. power)	8,473,324	
Annual Purchased Power, $/yr (100% CF)	53,368,636	
First Year Feedstock Cost, $/yr (100% CF)	20,236,208	
First Year Fixed O&M Cost, $/yr	7,145,223	
Total Plant Cost, $/yr	230,426,191	
Total Overnight Cost, $/yr	308,846,914	

3.5.2 Performance Metrics

3.5.2.1 CO_2 Conversion Efficiency

CO_2 conversion (CO2C) efficiency is defined as the amount of CO_2 utilized (CO_2 in – CO_2 out) on a mass basis per unit amount of CO_2 fed to the CO2C process. This represents the simplest way of thinking about a carbon conversion metric. It is a dimensionless ratio and is preferably expressed as a percentage. The higher the percentage, the more efficient the carbon conversion process.

For a continuous flow process, this metric is expressed as the flow rate of CO_2 into the process minus the flow rate of CO_2 leaving the process divided by the flow rate of CO_2 into the process.

$$CO_2\ Conversion\ Efficiency\ (\%) = \frac{Tonne\ CO_2\ Utilized}{Tonne\ CO_2\ Fed\ to\ Process} x\ 100$$

$$= \frac{(Tonne/Year\ CO_2\ In - Tonne/Year\ \ CO_2\ Out)}{Tonne/Year\ CO_2\ In}\ x\ 100$$

Example: A MW-DRM reactor system is fed 203,845 tonnes per year of CO_2. Total CO_2 emitted and captured from this process adds up to 141,500 tonnes per year of CO_2.

$$CO_2\ Utilized\ (Tonne/Year) = 203{,}845\ Tonne/Year\ CO_2 - 141{,}500\ Tonne/Year\ CO_2$$
$$= 62{,}345\ Tonne/Year\ CO_2$$

$$CO_2\ Conversion\ Efficiency\ (\%) = \frac{62{,}345\ Tonne/Year\ CO_2}{203{,}845\ Tonne/Year\ CO_2} x\ 100 = 30.6\%$$

3.5.2.2 CO_2 Conversion Potential

CO2C potential is the amount of CO_2 that would be utilized (CO_2 in – CO_2 out) on a mass basis to meet the desired product's market demand, relative to the amount of CO_2 emitted from a user-specified reference CO_2 emitter or plant. This metric represents the potential of a carbon conversion 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 CO_2 emission stream reference basis should be defined, since the metric is dependent on this reference, e.g., a single power plant emission or total U.S. coal-fired power plants emissions. Furthermore, the reference CO_2 basis can be further defined as the CO_2 emitted, or as the CO_2 captured in a carbon capture scenario. In the latter definition, the CO_2 captured represents the CO_2 available to the CO2C process.

$$CO_2\ Conversion\ Potential\ (\%) = \frac{Tonne/Year\ CO_2\ Utilized\ to\ Meet\ Market\ Demand}{Tonne/Year\ CO_2\ Available\ from\ Reference\ Plant} x\ 100$$

Example: The market demand of MeOH in North America was 8,394,000 tons (7,615,000 tonnes) in 2020 [13]. If a MW-DRM system produced enough MeOH to meet this demand, CO_2 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 CO_2 as the reference basis.

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

If the entire U.S. fleet of pulverized coal power plants were considered in place of the individual plant, the total CO_2 emissions would be 956,652,000 tonnes per year.

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

3.5.2.3 CO_2 Conversion Intensity

CO2C intensity is the amount of CO_2 utilized (CO_2 in – CO_2 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).

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

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

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO_2. The system produces 61 M gallons per year of MeOH, which is equivalent to 182,650 tonnes per year.

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

3.5.2.4 CO_2 Conversion Integration Reaction Rate

The CO_2 integration reaction rate is the molar rate of CO_2 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.

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

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO_2 (356.3 lbmol per hour). Assume the volume of the MW reactor is 1,000 gallons (a purely hypothetical value).

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

3.5.2.5 CO_2 Energy Conversion

The CO_2 energy conversion metric is defined as the net amount of energy required per unit amount of CO_2 utilized (mass basis). It is a measure of the energy efficiency of the technology or process to utilize CO_2. The units for the energy conversion metric are kW/(tonne CO_2 per hour).

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

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO_2. The normalized microwave efficiency of the reactor is 3,024 kW per tonne per hour of reactor inlet CO_2. The system is fed 203,845 tonnes per year of CO_2.

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

3.5.2.6 Notional Energy Penalty

The notional energy penalty (NEP) metric uses the enthalpy change of the CO_2 conversion reaction as a marker to identify energy intensive technologies. The equation describing this metric is shown here:

$$NEP \equiv \Delta H^o_{rxn} - Q_{NZCS}$$

where ΔH^o_{rxn} is the enthalpy change of the reaction to convert CO_2 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 CO_2 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 may be necessary to give context to the 100 kJ/mol CO_2 converted baseline.

3.5.3 Cost Metrics

3.5.3.1 Required Purchase Price of CO_2

The first program metric is the required purchase price of CO_2 (RPP). This metric represents the price at which the carbon conversion technology can afford to purchase CO_2 from the CO_2 producer and remain cost competitive with the current state of the art production method. The total cost to the carbon conversion 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 CO_2, the capital charges involved with producing the product, which include return on investment for the carbon conversion plant, the fixed operational costs, and the variable costs aside from the fluctuating cost of CO_2. The formula to calculate RPP is shown here:

$$\begin{Bmatrix} Required\ Purchase \\ Price\ of\ CO_2 \end{Bmatrix} \equiv \begin{Bmatrix} Product \\ Sale\ Price \end{Bmatrix} - \begin{Bmatrix} Capital \\ Charge \end{Bmatrix} - \begin{Bmatrix} Fixed \\ Costs \end{Bmatrix} - \begin{Bmatrix} Variable\ Costs \\ Excluding\ CO_2 \end{Bmatrix}$$

To create a meaningful result for RPP, the cost information used should be reliable and well-described, which may be difficult for low-technology readiness level 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 carbon conversion to be economically feasible, the RPP should meet the cost of capture of CO_2.

Example: A MW-DRM reactor system produces 61 M gallons per year of MeOH at a breakeven levelized cost of $1.86 per gallon when CO_2 is assumed to be free. The MW-DRM reactor system takes in 224,623 tons per year of CO_2. The total cost excluding CO_2 can then be calculated.

$$\begin{Bmatrix} Total\ Cost \\ Excluding\ CO_2 \end{Bmatrix} = \begin{Bmatrix} Capital \\ Charge \end{Bmatrix} + \begin{Bmatrix} Fixed \\ Costs \end{Bmatrix} + \begin{Bmatrix} Variable\ Costs \\ Excluding\ CO_2 \end{Bmatrix}$$
$$= \frac{61\ M\ Gallons/Year\ x\ \$1.86/Gallon}{224{,}623\ Ton\ CO_2/Year} = \$505.11/Ton\ CO_2$$

The market price for MeOH 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.

$$\begin{Bmatrix} Product \\ Sale\ Price \end{Bmatrix} = \frac{\$92{,}120{,}554/Year}{224{,}623\ Ton\ CO_2/Year} = \$410.11/Ton\ CO_2$$

The required purchase price of CO_2 can then be calculated.

$$\left\{\begin{matrix} Required\ Purchase \\ Price\ of\ CO_2 \end{matrix}\right\} \equiv \left\{\begin{matrix} Product \\ Sale\ Price \end{matrix}\right\} - \left\{\begin{matrix} Capital \\ Charge \end{matrix}\right\} - \left\{\begin{matrix} Fixed \\ Costs \end{matrix}\right\} - \left\{\begin{matrix} Variable\ Costs \\ Excluding\ CO_2 \end{matrix}\right\}$$
$$= \$410.11/Ton\ CO_2 - \$505.11/Ton\ CO_2 = -95.00\ \$/Ton\ CO_2$$

This result suggests that a credit of \$95 per ton of CO_2 must be applied for this process to be cost competitive with the current state of the art production methods.

3.5.3.2 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.

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

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

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

3.5.3.3 Cost per Tonne of CO_2 Utilized

The cost per tonne of CO_2 utilized metric is the sum of annualized capital and operating costs of the carbon conversion process relative to the tonnes of CO_2 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 dollars per tonne of CO_2. 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 carbon conversion pathway should be more cost effective than the process it aims to replace.

$$Cost\ per\ Tonne\ CO_2\ Utilized\ (\$/Tonne) = \frac{\sum Annualized\ Capital\ and\ Operation\ Costs\ (\$/Year)}{Tonne/Year\ CO_2\ Utilized}$$

Example: A MW-DRM reactor system utilizes 62,345 tonnes per year of CO_2. The TPC is \$230,426,191 per year.

$$Cost\ per\ Tonne\ CO_2\ Utilized\ (\$/Tonne) = \frac{\$230{,}426{,}191/Year}{62{,}345\ Tonne\ CO_2/Year} = \$3{,}696/Tonne\ CO_2$$

3.5.3.4 Incremental Cost Reduction

If there is a traditional process for making the desired product that the new carbon conversion process is replacing, then the incremental cost reduction metric is the incremental reduction in cost by the new carbon conversion process over the traditional process. This metric builds on the previous Cost per Ton CO_2 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.

$$Incremental\ Cost\ Reduction\ (\$/Tonne) = ((\$\ Cost\ to\ Make\ a\ Tonne\ of\ Product\ by\ Traditional\ Process) - (\$\ Cost\ to\ Make\ a\ Tonne\ of\ Product\ by\ New\ Process))$$

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

$$Incremental\ Cost\ Reduction\ (\$/Tonne) = \$297/Tonne\ MeOH - \$621/Tonne\ MeOH = -\$324/Tonne\ MeOH$$

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

3.5.4 Emissions Metrics

3.5.4.1 CO_2 Emission Metric

CO_2 emission metric is the CO_2 emissions of the new carbon conversion pathway versus the CO_2 emissions of the traditional pathway. The new process must reduce the overall CO_2 emissions.

$$CO_2\ Emission\ Metric = \frac{Tonne\ CO_2\ Emission\ in\ New\ Process}{Tonne\ CO_2\ Existing\ or\ Traditional\ Process}$$

Example: A MW-DRM reactor system emits 141,500 net tonnes per year of CO_2. A separate MeOH-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 CO_2.

$$CO_2\ Emission\ Metric = \frac{141{,}500\ Tonne\ CO_2/Year}{30{,}444\ Tonne\ CO_2/Year} = 4.65$$

This result suggests that the MW-DRM reactor system does not reduce overall CO_2 emissions.

3.5.4.2 CO_2 Emissions Reduction

If there is a traditional process for making the desired product that the new carbon conversion process is replacing, then the CO_2 emissions reduction metric is the amount of CO_2 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 CO_2 emissions reduction.

$$CO_2\ Emission\ Reduction\ (\%) = \frac{Tonne\ CO_2\ Emission\ Reduction}{Tonne\ CO_2\ Existing\ Emissions} x\ 100$$

$$= \frac{(Tonne/Year\ CO_2\ Emitted\ in\ Existing\ Process - Tonne/Year\ \ CO_2\ Emitted\ in\ New\ Process)}{Tonne/Year\ CO_2\ Emitted\ in\ Existing\ Process}\ x\ 100$$

Example: A MW-DRM reactor system emits 141,500 net tonnes per year of CO_2. A separate MeOH-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 CO_2.

$$CO_2\ Emission\ Reduction\ (\%) = \frac{30{,}444\ Tonne\ CO_2/Year\ -\ 141{,}500\ Tonne\ CO_2/Year}{30{,}444\ Tonne\ CO_2/Year} x\ 100$$
$$= -365\%$$

This result suggests that the MW-DRM reactor system demonstrates an increase in CO_2 emissions of 365 percent.

3.5.4.3 CO_2 Avoided Potential

If there is a traditional process for making the desired product that the new carbon conversion process is replacing, then the CO_2 avoided potential metric is the amount of CO_2 avoided by the new process over the traditional process and assumed to offset CO_2 emissions from a user-specified reference CO_2 emitter or plant. This metric is a dimensionless ratio and should be expressed as a percentage. Put another way, the CO_2 avoided potential is the percentage of the reference plant CO_2 emissions that the new process would avoid producing, when considering the carbon conversion process and reference CO_2 emitter within the same envelope.

$$CO_2\ Avoided\ Potential\ (\%) = \frac{Tonne/Year\ of\ CO_2\ Avoided\ to\ Meet\ Market\ Demand}{Tonne/Year\ of\ CO_2\ Emitted\ from\ Reference\ Plant} x\ 100$$
$$= \frac{(Tonne/Year\ CO_2\ Emitted\ from\ Existing\ Process - Tonne/Year\ CO_2\ Emitted\ from\ New\ Process)}{Tonne/Year\ CO_2\ Emitted\ from\ Reference\ Plant}\ x\ 100$$

Example: The market demand of MeOH in North America was 8,394,000 tons (7,615,000 tonnes) in 2020. [13] If a MW-DRM system produced enough MeOH to meet this demand, net CO_2 emitted would be 5,899,000 tonnes per year. A separate MeOH-producing system uses an autothermal reformer in place of the MW-DRM reactor to produce syngas. If this system produced enough MeOH to meet demand, CO_2 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 CO_2 as the reference basis.

$$CO_2\ Avoided\ Potential\ (\%) = \frac{1{,}269{,}000\ Tonne\ CO_2/Year - 5{,}899{,}000\ Tonne\ CO_2/Year}{3{,}763{,}000\ Tonne\ CO_2/Year} x\ 100$$
$$= -123\%$$

This result suggests that the MW-DRM reactor system will not avoid CO_2 emissions if used in place of the traditional process.

3.5.5 Market Metrics

3.5.5.1 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.

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

Example: Assume that a MW-DRM reactor system utilizes the CO_2 emissions of a supercritical pulverized coal plant with 90 percent capture (Fossil Energy Baseline Case B12B). The amount of CO_2 emitted is 480,897 tonnes per year, limiting the potential MeOH production of the MW-DRM reactor system to 430,895 tonnes per year. The market demand of MeOH in North America was 8,394,000 tons (7,615,000 tonnes) in 2020.

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

3.5.5.2 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 carbon conversion technologies that are functionally identical to products currently in production that have the same end-use (e.g., MeOH for chemical use versus MeOH 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 may 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 may occur.

Example: The global production of MeOH was 106,598,000 tons (96,704,000 tonnes) in 2020. [13] At a market price of $488 per tonne, this corresponds to a yearly revenue of $47,192,000,000. [14] Assume a market penetration value of 20 percent.

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

3.5.6 Other Metrics

3.5.6.1 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 National Fire Protection Association Standard 704 "fire diamond" category hazard values, which range from 0 to 4, with 0 meaning no hazard and 4 meaning severe hazard. [15] The National Fire Protection Association 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. [16]

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.

3.5.6.2 Other Strategic Benefits

Externalities reflect qualitative policy judgments established by DOE Headquarters 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. [17] Externalities include the following:

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

4 TECHNO-ECONOMIC ANALYSIS TEMPLATE AND SUBMISSION GUIDANCE

4.1 TECHNO-ECONOMIC ANALYSIS TEMPLATE GUIDANCE

This section describes the reporting template that accompanies the guidance document. The purpose of the template is to streamline the reporting of the information requested in Section 3 and ensure that the same type/quality of information is being provided by each vendor. The template comprises a Microsoft Excel spreadsheet that is divided into six worksheets. Five of these worksheets provide blank tables and highlighted sections for the vendor to input the requested data for the model facility. These worksheets are titled Facility Description, Performance Analysis, Economic Analysis, Market Analysis, and Carbon Conversion Metrics; the data requested within each worksheet correspond to the given title. A sixth worksheet titled Conversion Factors includes conversion factors used throughout the spreadsheet and no information need be provided by the vendor within this worksheet. This is the format requested for the submission of TEA-related materials. Further guidance on using the template (included required reporting units) is included in Section 3 and within the template itself.

4.2 SUBMISSION GUIDANCE

Submission of techno-economic analysis information by the vendor is voluntary; the information is not required but may be submitted in addition to the vendor's Life Cycle Analysis (LCA) submission. Submitting techno-economic analysis information (or opting not to) will have no impact on the critical review of the LCA. Although demonstration grants under the FOA will be restricted to eligible entities (States, local governments, and public utilities or agencies), these eligible entities need to procure and use commercial or industrial products derived from anthropogenic carbon oxides. These products must demonstrate significant net reductions in life cycle greenhouse gas emissions compared to incumbent technologies, processes, and products. If a carbon conversion product manufacturer would like to be listed as an eligible vendor, they must satisfactorily completed a critical review of a life cycle analysis completed in accordance with UPGrants-specific LCA guidance. Additionally, carbon conversion product manufacturers may choose to submit data related to techno-economic analysis and community benefits, which will facilitate DOE further development of the Carbon Conversion Program.

Carbon conversion product manufacturers can submit documents prepared in accordance with the preceding guidance through the UPGrants submission page.

4.3 PROTECTION OF PROPRIETARY INFORMATION

Federal employees are obligated to not disclose any confidential information under 18 U.S.C. 1905. The information in the submission could be subject to release under the Freedom of Information Act; however, it may fall under a Freedom of Information Act exemption (e.g., Exemption (b)(4), which allows an agency to withhold trade secrets and commercial or financial information, obtained from a person, which is privileged and confidential), but DOE cannot guarantee up front that the information will be exempt. Whenever a document submitted to DOE by a private business contains information that may be exempt from public disclosure, it will be handled in accordance with the procedures in 10 CFR 1004.11. While DOE is responsible for making the final determination with regard to the disclosure or nondisclosure of information contained in any requested documents, DOE will consider the submitter's views in making its determination. If the submitter believes the information submitted would constitute trade secrets or commercial/financial information that is privileged and confidential, it is often recommended that the submitter label the documents as such.

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