Workshop on LCA/TEA for CO_2-based Products

Organized and hosted by the Global CO_2 Initiative in partnership with the National Energy Technology Laboratory (NETL), the National Renewable Energy Laboratory (NREL), and Volans. Held on April 10th and 11th, 2019, Ann Arbor, Michigan, USA in the Gerald R. Ford Presidential Library.

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Abstract

On April 10th and 11th of 2019, a group of about 100 academics, industry experts, government officials, policymakers, and nonprofit representatives gathered at the University of Michigan in Ann Arbor to participate in a workshop focused on topics related to the creation of streamlined life cycle assessment (LCA) and techno-economic assessment (TEA) guidelines for emerging carbon dioxide and monoxide ('carbon' in the following) capture and utilization (CCU) technologies. This report summarizes the key takeaways from this workshop.

Carbon utilization differs from mere sequestration of carbon in geologic reservoirs as utilization yields a product with a level of economic value. This feature will ideally allow CCU technologies to be scaled quickly through commercialization. Scaling will make them an important component in the portfolio of tactics in the pursuit to reduce greenhouse gas emissions. Utilization is also representative of a circular economy and, depending on the process, may offer additional environmental benefits.

CCU technologies are generally early in development and often have low technology readiness levels (TRLs). Thus, customized LCA and TEA guidelines are needed to offer direction on assessing their viability with a reasonable degree of certainty. Such guidelines are of course still required for technologies at all TRLs.

The Global CO_2 Initiative has developed an initial version of LCA and TEA guidelines specifically for use in evaluating CCU technologies. The participants find the LCA guidelines consistent with those produced by the National Energy Technology Laboratory (NETL) and the TEA guidelines consistent with those developed by the National Renewable Energy Laboratory (NREL). However, they suggest additional work during the next few years as part of the "CO_2nsistent" project – which is funded by the Global CO_2 Initiative and EIT Climate-KIC – to create guidelines that will be more relevant to, and more comprehensible by, non-technical stakeholders than the existing guidelines while still fully addressing system boundaries and benchmark product comparison. This focus on clear communication of LCA and TEA results to audiences made up of non-technical stakeholders is of paramount importance, as these stakeholders are often involved in downstream decision-making processes about project investment.

In addition to being generally comprehensible, the end results of LCAs and TEAs for CCU technologies must also account for uncertainties in both the energy and material inventory as well as the technological parameters using uncertainty analysis. These results should also incorporate sensitivity analysis, which quantitatively assesses the sensitivity of key indicators to changes in inventory data, and scenario analysis, which reflects the potential results of various possible realities within a given scope.

Finally, as the utilization of carbon dioxide is a global opportunity and emissions are a global problem, the developing LCA/TEA guidelines will have to consider international perspectives. Ideally, the resulting guidelines will be informed by input from individuals and organizations in all parts of the world and be relevant to researchers and decision makers with varying national requirements.

Introduction

Along with other approaches to furthering the critically needed reduction of atmospheric CO_2 levels, new strategies for treating waste CO_2 are increasingly needed. Among the most promising of these are carbon capture and utilization technologies, which incorporate processes to transform waste carbon dioxide into useful products available for purchase by global commercial entities and private citizens. While sequestration of carbon in geologic reservoirs contributes to CO_2 removal efforts, it does not, with the exception of Enhanced Oil Recovery (EOR), yield a product with economic value. Thus, the quest to develop technologies that are both carbon reducing – providing a CO_2 reduction benefit over existing technologies that make the same or similar products – and dollar positive – creating an economic incentive for development, scale-up, deployment, and prosperous operation – is intensifying.

Because this economic incentive encourages industry adoption of environmentally beneficial operations through targeted build-up of sustainable economic opportunities, CCU technologies are an important complement to energy efficiency improvements, transitions to renewable energies such as wind and solar, and other emissions reductions efforts. Like these, they address the urgent need for action to help counter negative effects of climate change. In response to the challenges and opportunities presented by this need, new technologies for CO_2 capture, conversion, and utilization for sustainable products are being explored in an increasing number of research and production projects around the world.

In this context, assessment of new CCU technologies is essential for accurate prediction and evaluation of their environmental and economic benefits and risks. Life cycle assessment (LCA) and techno-economic assessment (TEA) are procedures that can provide this information and guide decisions about which technologies merit commercializing into the marketplace. However, such assessments are complex, depend on boundary conditions, are impacted by local regulations and laws, and often suffer from incomplete information, especially when conducted for technologies at an early stage of their development (i.e., with a low level of technology readiness, including Technology Readiness Levels (TRLs) 1 through 3). Consequently, it is hardly surprising that problems associated with their use arise. For example, comparisons of assessment results can lead to incorrect interpretations if these results were obtained by different assessors, were performed with varying methods, or employed methods that are either too generic or were defined for other product categories. CO_2 utilization (CO2U) is a new actor on the global stage, and those who are leading its development must ensure that a common language and set of technology evaluation tools be available for use by companies, researchers, and policymakers working in this emerging space.

To address the need for harmonization of procedures for LCA and TEA for CCU and for consistent interpretation and reporting of the results, the Global CO_2 Initiative held a workshop at the University of Michigan, Ann Arbor on April 10th and 11th, 2019. The workshop, which was planned and hosted in partnership with the National Energy Technology Laboratory, the National Renewable Energy Laboratory, and Volans, was convened to provide opportunities for discussion of differences and commonalities between various LCA and TEA approaches and identification of action items for further harmonization.

About 100 academic, industry, policy, and civil society experts working in the carbon dioxide capture and utilization space gathered at this workshop to explore CO_2 metrics, best practices, validation, and next steps. The participation of industry and policy experts was sought for the facilitating of stakeholder input to maximize acceptance and usability of the new technologies. The ultimate goal of the discussions was to begin crafting a harmonized global toolkit for measuring and reporting on carbon dioxide utilization or removal technologies for project investment, product marketing, and policy needs. This toolkit may include a number of guidelines that are adapted to local policy requirements while at the same time remaining compatible in their approaches and reporting to allow transparent evaluation across the entire field. The payoff for these efforts is clear: comprehensive, consistent, and transparent LCAs/TEAs and reporting of their results will accelerate funding decisions and promote sustainability-driven technology development.

This report presents the most important takeaways from this workshop. It begins by presenting the conclusions from a discussion and evaluation of existing LCA/TEA guidelines in Section 1, noting where these are already harmonized and where further harmonization might be helpful. Section 2 summarizes the discussion of the need for streamlined guidelines specifically designed for low-TRL technologies. Sections 3 and 4 present the substance of discussions addressing problems associated with the interpretation and communication of the results of LCA and TEA for various audiences. Section 5 summarizes the discussion of the need for contextualization of reports so that the feasibility of 'go/no-go' decisions can be assessed; it also identifies some difficulties associated with the process. The final section presents the key conclusions from a discussion of the need for international perspectives in the development of CCUs.

1. No Major Flaws Identified in the Guidelines

The Global CO_2 Initiative and NETL have completed first versions of guidance documents intended to advise on the execution of TEAs and LCAs for CCU projects. The Global CO_2 Initiative provides general TEA and LCA guidance for CCU projects to the global community, and NETL provides LCA guidance specific to United States (U.S.) funding recipients that are required to report to the U.S. Department of Energy (DOE). Both NETL and NREL have developed best practices for TEA of CCU technologies but have not yet formalized these recommendations in a specific guidance document. The workshop participants did not identify any major flaws in the guidelines developed thus far, but they noted opportunities for further standardization.

LCA Guidance Documents

The Global CO_2 Initiative and NETL agree that their LCA guidance documents do not differ substantially. Both follow ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines) and provide additional guidance specific to CCU projects. The NETL document goes a step further and provides more specific guidance related to the program goals of the U.S. DOE Carbon Use and Reuse program (i.e., specification of coal-fired power plants as the source of CO_2). In addition to following International Organization for Standardization (ISO) standards, both documents (a) favor system expansion as a co-product management method, (b) require that the source of the CO_2 be included in the system boundary, (c) acknowledge that the primary research question will likely involve the comparison of a CCU system and a reference system, (d) use similar classifications for technology readiness levels (TRLs), and (e) assign a multi-product functional unit based on technical equivalency.

The documents differ primarily in their suggested data sources for impact assessment and inventory. The Global CO_2 Initiative suggests CML for global applications and Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) v2.0 for U.S. applications. The Global CO_2 Initiative also includes standardized scenarios for CML results: status-quo, low decarbonization, high decarbonization, and full decarbonization. NETL guidance is U.S.-based only and requires TRACI v2.1. For inventory data, NETL requires funding recipients to use NETL data for some of the processes in their main scenario. The Global CO_2 Initiative does not require particular inventory data but does provide thinkstep data – through impact assessment – for some inputs (e.g. electricity, hydrogen, and natural gas).

TEA Guidance Documents

While TEA is a widely-used tool, guidelines for completing a TEA can vary according to application, technology development, and stakeholder needs. The approaches presented at the workshop by the Global CO_2 Initiative and NREL for TEA of CCU technologies are generally consistent with each other. While NETL did not present specific TEA guidance at the workshop, NETL completed a point-by-point review of the Global CO_2 Initiative TEA guidance and saw general agreement with the methods presented.

The Global CO_2 Initiative's guidance document on TEA gives generic advice for a global audience, leaving room for the use of specific scenarios and methods if desired. NREL's methods are often designed to, but not limited to, work closely with funded technology developers within DOE-funded programs to conceptualize the performance and costs of their process in relation to DOE goals. NETL's approach is similar to NREL's approach in practice by informing technology developers throughout the development process from early research to commercialization. Several sources for cost of electricity, cost of capture, and metrics to assess CCU technologies are publicly available from NETL; these can be incorporated into TEA for CO_2 utilization. [See literature section of this report]

Both NREL and NETL provide TEA guidance for early-stage development technologies (for definition of the development stages, see footnote 1) within DOE-funded programs to provide screening-level information, while the Global CO_2 Initiative guidelines document is used to inform the detailed analysis of a technology on the basis of audience needs. The three-year project "CO_2nsistent," funded by the Global CO_2 Initiative and EIT Climate-KIC, will also expand the TEA guidance document to address low technology-readiness level (TRL) projects. Both the Global CO_2 Initiative and NREL use performance and cost-curves to project a potential future state for the given technology. NETL is seeking to standardize the application of learning curves, among other TEA metrics, for low-TRL technologies via a guidance document that is currently in development and is on track to be released in 2020.

2. The Need for Streamlined LCAs for Low-TRL Projects

As noted previously, the assessment and evaluation of early-stage and low TRL CCU projects pose particular difficulties. Conventional LCA and TEA methods require large amounts of data and substantial time and effort. Such data is typically not available at high accuracy for technologies in the early- to mid-stages of development (TRL 1 to TRL 6). The application of conventional LCA and TEA methods is thus challenging. Nonetheless, crucial decisions regarding the viability and probably suitability for commercialization must be made. The workshop community identified a need for "streamlined" assessment that would enable reasonably certain assessment results with less effort in general and for technologies at an early stage in their technological maturity. Such streamlined assessments could guide R&D activities intended to bolster economic and environmental benefits and support the making of sound funding decisions by governmental entities, corporate R&D departments, and early-stage investors.

The workshop community observed that such methods, though nominally available, are of unsatisfactory quality. In current best practice, researchers are discussing various approaches to the streamlining of early stage technology assessment, including thermodynamic shortcuts, approximated process design, and artificial neural networks. The community recognizes that the application of these quicker or reduced-effort approaches will result in a trade-off between effort and data requirements on the one hand and certainty of the results on the other hand. Furthermore, the same category of data might have varying levels of certainty for different technologies. Uncertainties can also vary substantially across product life cycle phases and comparative reference processes for both environmental impact categories and economic metrics.

Ways of describing and dealing with these uncertainties must be addressed in detail in the creation of a suitable methodology and set of useful assessment indicators for low-TRL project assessments. The joint project by the Global CO_2 Initiative and EIT Climate-KIC "CO_2nsistent" is focusing on the development of streamlined assessment approaches that will clearly describe such uncertainties and offer suggestions for handling them.

3. The Need for Guidelines for Successful Interpretation of LCA/TEA Results

In most cases, the results of LCA and TEA conducted for the assessment of promising CCU projects are expected to have multiple recipients. This audience, generally referred to as stakeholders, could include policymakers and associated staff, investors (both internal and external to an organization), R&D program managers, researchers, corporate managers, and consumers (especially from the perspective of product labeling). The stakeholders constituting each of these groups have slightly different needs depending on their role in general and within their organizations. Practical use of the reported results, however, poses a significant barrier to many in their intended audience. Practitioners agree that LCA and TEA are complex and that their results require significant effort to properly interpret. In response to the recognition of these difficulties, workshop participants expressed the desire for a companion document or section to provide guidance on structuring results for those on the receiving ends of TEA and LCA reports and analyses.

Because the LCA/TEA guidelines developed by the Global CO_2 Initiative and the LCA guidelines developed by the NETL are written primarily with an audience of engineers and analysts in mind, non- and less-technical stakeholders need to be made aware of factors that affect interpretation of the results, including the key methodological decisions made to ensure that the study results are valid for the intended application and directly comparable to other reports. Guidelines for conducting LCA and TEA are designed to prevent the manipulation of the analysis to yield biased results; however, potential pitfalls remain for stakeholders in the interpretation of these analysis results.

When evaluating LCA results, stakeholders should be cognizant of the following:

- The system boundaries are complete and include the source of the CO_2 for the utilization project; and
- Multifunctionality is an inherent characteristic of CCU systems, which requires thoughtful development of comparison/benchmark systems to assess potential benefits.

Although the workshop was focused more on LCA than on TEA (because guidance documents for LCA have recently been released by both the Global CO_2 Initiative and NETL, while TEA guidelines are available only from the Global CO_2 Initiative), standard TEA methodology used by the NREL was presented to serve as a basis for discussion. Importantly, the various classes (Class 1 –5, See Literature Section) of TEA were introduced. The classes are differentiated according to the purpose of the analysis (especially for different TRLs), the accuracy, the exact methodology, and the time or budget requirement.

The key takeaways from the discussion of TEA methodology are these:

- TEA is a methodology utilized by governments, industries, and academia to analyze the impact of research discoveries and engineering advances on the economic viability of an individual process elements, a system of integrated processes, or even a whole value chain. When effectively coupled with research and development (R&D) efforts, TEA is an important complementary tool for understanding and identifying key process attributes that affect overall production costs or market/business model assessments.
- Performance of TEA over a range of technology readiness levels (TRLs) requires the application of different analysis strategies (Classes 1 - 5 as noted above) in an iterative effort between the analysis team, the R&D team and the key stakeholders. The level of rigor required for a TEA is dependent on both the stage (class) of the TEA effort and the number of iterations with collaborating teams.
    - TEA of low-TRL technologies to validate an initial idea focuses on determining primary and auxiliary equipment costs using factored design estimates. These estimates utilize a range of heuristics and cost curves to calculate costs from data available in the public domain (e.g., reference books and software).

    - TEA of high-TRL technologies uses more rigorous process designs and economic evaluations. In these cases, it is imperative that the TEA team work with trusted vendors to develop detailed process designs and estimate equipment manufacturing capital cost, including detailed cost estimates for all core conversion equipment as well as all auxiliary equipment, control systems, and safety components.
- Collaboration with engineering and construction firms to enhance credibility and quality as well as iteration with researchers, experimentalists, and key stakeholders are essential to perform accurate TEA.
- Workshop participants concluded that TEA analysts are speaking a *similar* language (albeit many different approaches, concepts and indicators have been reported in TEAs for CCU) and are aware of many of the other major analysis groups working in the CO_2 utilization space.

While no major flaws in existing TEA methodology and guidance were identified during the workshop, the discussants generally agreed that guidance for the interpretation of TEA would benefit the community by heading off common pitfalls and miscommunications. The group identified eight tasks that are critical to the development of guidelines for successful interpretation of TEA results:

- Establish generally accepted approaches (i.e., frameworks or methodologies) for TEA.
- Differentiate TEA from business cases; the two have different intended uses.
- Define and provide the class/stage of the TEA analysis, e.g., hot-spot analysis for low- TRL technologies vs. in-depth process design and cost determination for high-TRL technologies. The classification of a TEA into one of the 5 classes would guide its interpretation/use. The uncertainty of the assessment is bounded not only by TEA classification, but also by input data, model structure and contents.
- Harmonize nomenclature across various TEA guidelines, existing and emerging.
- Ensure that guidelines for interpretation take international perspectives and needs into consideration, such as differences in taxation laws.
- Define broadly-applicable approaches and methods for linking TEA and LCA through common metrics, especially for highlighting direct and indirect relationships (e.g., trade-offs).
- Provide scenario analysis and sensitivity analysis to avoid the pitfall of focusing too much on a singular cost value (i.e., the inherent value of TEA lies not in the exact cost output, but in the insight provided into the key cost drivers).Analyze and report uncertainty in cost estimates, especially for low-TRL technologies and unit operations that are not yet commercial.
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4. How to Communicate LCA/TEA Results Clearly

Clear communication of results is vital to maximize the usefulness of any LCA or TEA study. The method of communication should be designed to suit the target group and the specific needs of its members. In many cases, a non-practitioner will be involved in the eventual decision-making process, and thus the outcomes of the study must be easy to understand by diverse audiences with varying levels of technical expertise. The underlying scenarios, basic assumptions, and limitations of the study must be explained clearly and concisely, as these have a large impact on the interpretation of the results. The workshop group recommends that further work be undertaken to provide guidance on what can be expected from a study and on the communication of study results.

Furthermore, guidance is needed to help commissioners of studies and decision-makers determine necessary aspects for the scope of the study to ensure study that outcomes are relevant, interpret a study, and make qualified statements from quantified outputs. This guidance is vital, because often the LCA or TEA practitioners who conduct the study are not the decision-makers who will have to use the outcomes and results as the basis for their decision-making.

The vocabulary relevant to discussion of CCUs requires standardization. Clear definitions of terms such as *carbon neutral* and *carbon negative* are needed to ensure consistent and effective communication of results. The group recommends the creation of a standardized, globally applicable vocabulary/nomenclature for carbon utilization studies. The initial work on this will be included in the scope of the CO_2nsistent project.

5. Putting Results in Context for “Go/No-Go” Decisions

The goal and scope, the system boundary, the energy and material inventory, and the technological parameters provide the context in which an LCA or TEA is conducted for CCU technologies. Clear reporting of the context of the TEA and the LCA ensures that all stakeholders, even those without a background as practitioners, can correctly interpret the results of a given study and provide an assessment on whether or not a technology offers development or deployment potential and under which circumstances, e.g., supply of energy from renewable sources.

Assumptions made about key components of carbon utilization projects, such as the carbon capture technology used, the allied processes that enable CO_2 utilization such as hydrogen production, the electricity grid mix, and the product for which the CO_2 is utilized ultimately have significant impact on the reported environmental and economic viability. Thus, they need to be clearly reported. Furthermore, LCAs and TEAs of CCU that involve the use of renewable energy to produce hydrogen (e.g., “power to X technologies”) should account for the economic or environmental opportunity cost of the renewable energy being supplied to the grid or used in competing technologies to offset CO_2 emissions from fossil electricity that would have been used otherwise.

In situations in which "go/no-go" decisions are being considered for low-TRL processes, a means of accounting for the impact of uncertainties is needed. Uncertainties in the material and energy inventory and technological parameters are especially typical in the so-called "valley of death" (TRLs 4 to 6). To increase confidence in the recommendation of the LCA or TEA, sensitivity analysis can be incorporated to explore and rigorously evaluate the impact of uncertainties, not only those indicated previously but also other values in the inventory data, such as CCU technology parameters, grid mix electricity, and allied technology systems (e.g. hydrogen production), on the viability of the overall technology.

Practitioners can also apply scenario analysis to LCAs and TEAs in order to reflect the known or expected realities of the time period and geographical location considered within the study. In general, in cases in which a technology is assessed in a scenario in which it is enabled by unrealistic, unlikely, or highly contingent developments, a "go/no-go'" decision should not be made. However, a distinction could be made among scenarios involving presently unrealistic developments; scenarios in which it is a reasonable assumption that the problems can be solved might be allowed. Ensuring that key components are both clearly reported and assessed with a clearly defined level of sensitivity permits other stakeholders to ascertain how reliable a "go/no go" decision may be and thus whether or not such a decision is feasible. In a case in which a technology is assessed as viable in a scenario that remains unrealistic from a technological, economical or environmental perspective, a 'go/no-go' decision is infeasible.

Economic and environmental hotspots for the CCU technology can be identified for different scenarios. These hotspots are critical parameter uncertainties that impact the "go or no-go" decision. Approaches to include the impact of uncertainty can improve confidence in the economic and environmental performance of the CCU technology. Sensitivity analysis and, in particular, scenario assessment also provides opportunities to conduct environmental and economic break-even analyses under different technology improvement pathways, identify strategies to shorten break-even periods, and construct economically and environmentally sustainable pathways for commercialization of the CCU technology. Ideally, these opportunities will provide stakeholders with the information necessary to compare the viability of different CCU technologies given different societal developments.

Well-contextualized outputs from LCA and TEA studies should ease the burden on stakeholders who make decisions, such as technology managers and policymakers. These outputs should communicate the impacts of variability and sensitivity on the technology clearly while providing guidance on the feasibility of making a "go/no-go" decision.

6. Incorporating International Perspectives & Establishing Coordination

Carbon capture and utilization technologies represent a global opportunity albeit with some local differences. Thus, those researchers who are developing methods for LCA and TEA must take international perspectives into account. Although the majority of the participants of this workshop were from either North America or Europe, participants recognized the need to incorporate a wider global perspective in order to have the highest impact possible.

Incorporation of an international perspective into the development of CCU has two key facets:

1. Researchers in other parts of the world have already made significant progress and gained valuable experience in CCU. Learning what has already been attempted and achieved will be valuable for the evolution of the methods.
2. To have the greatest possible impact, methods will need to be globally relevant so that all regions can use them in developing these technologies. Worldwide applicability will also permit streamlined comparisons of carbon capture technologies from around the world.

Next steps should include undertaking research to identify key regions, relevant examples, and potential contacts and then inviting relevant stakeholders to ongoing engagement, both virtual and in-person, in the development and deployment of the guidelines. The biannual workshops conducted by the Global CO_2 Initiative and Climate-KIC could be a suitable venue for the in-person interactions.

While LCA and TEA are specific, defined methods in and of themselves, their use can be widened and their processes improved through interaction with other initiatives and organizations whose outputs, methods, and feedback are relevant to the performance of LCA and TEA. Participants recognized that engaging with relevant organizations throughout this process will be important so that wherever possible, existing benchmarks, scenarios, or other common references may be noted and leveraged.

Following is a list of some of these relevant organizations:

- World Resources Institute (WRI) – This non-profit institution may be revising the Greenhouse Gas (GHG) protocol to more thoroughly incorporate carbon capture and utilization.
- Task Force on Climate-related Financial Disclosures (TCFD) – This body references a series of scenarios.
- Emissions Reduction Alberta (ERA) – This group is funding a project to develop models for assessment of early-stage CCU technologies.
- The IEA Greenhouse Gas R&D Programme (IEAGHG) – This program has the explicit goal of facilitating international collaborative R&D activities centered on reducing greenhouse gas emissions.
- European Commission/Phoenix Initiative – Supported by the EU member states, this program serves to link national and European activities surrounding carbon dioxide valorization.

Literature and Definitions

Global CO_2 Initiative guidelines and examples of executed TEAs and LCAs

Guidelines: https://deepblue.lib.umich.edu/handle/2027.42/145436
Methanol Example: https://deepblue.lib.umich.edu/handle/2027.42/145723
Mineralization Example: https://deepblue.lib.umich.edu/handle/2027.42/147467
OME Example: https://deepblue.lib.umich.edu/handle/2027.42/147468

NETL LCA/TEA toolkit and resources

CO2U LCA Toolkit: www.netl.doe.gov/LCA/CO2U
LCA Resources: www.netl.doe.gov/LCA
TEA Resources: www.netl.doe.gov/EA/about
Cost and Performance Baseline Studies: https://www.netl.doe.gov/energy-analysis/details?id=729
Cost of Capturing CO2 from Industrial Sources Report: https://www.netl.doe.gov/energy-analysis/details?id=1836
FE/NETL CO2 Transport Cost Model and User's Manual: https://www.netl.doe.gov/energy-analysis/details?id=630
Quality Guidelines for Energy System Studies (QGESS): Cost Estimation Methodology for NETL Assessments of Power Plant Performance: https://www.netl.doe.gov/energy-analysis/details?id=790
QGESS: Capital Cost Scaling Methodology: https://www.netl.doe.gov/energy-analysis/details?id=1026
Cost and Performance Metrics Used to Assess Carbon Utilization and Storage Technologies: https://www.netl.doe.gov/energy-analysis/details?id=737

NREL LCA/TEA documentation

Techno-Economic Analysis: https://www.nrel.gov/analysis/techno-economic.html
Techno-Economic, Sustainability, and Market Analysis: https://www.nrel.gov/bioenergy/economic-sustainability-market-analysis.html

TEA Classes 1-5: https://web.aacei.org/docs/default-source/toc/toc_18r-97.pdf?sfvrsn=4.

Technology readiness levels (TRL), as defined by the U.S. Department of Energy and the European Commission Horizon 2020 Program, are numbered 1 through 9 and are grouped into three phases.
Research Phase: (1) idea, (2) concept, (3) proof of concept
Development Phase: (4) preliminary process development, (5) detailed process development, (6) pilot trials
Deployment Phase: (7) demonstration and full-scale engineering, (8) construction and start-up, and (9) continuous operation.