The need for and path to harmonized life cycle assessment and techno-economic assessment for carbon dioxide capture and utilization

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The use of carbon dioxide as a feedstock for a broad range of products can help mitigate the effects of climate change through long-term removal of carbon or as part of a circular carbon economy. Research on capture and conversion technologies has intensified in recent years and the interest in deploying these technologies is growing fast. However, a sound understanding of the environmental and economic impact of these technologies is required to drive fast deployment and avoid unintended consequences. Life cycle assessments and techno-economic assessments are useful tools to quantify environmental and economic metrics; however, these tools can be very flexible in how they are applied, with the potential to produce significantly different results depending on how the boundaries and assumptions are defined. Built on ISO standards for generic life cycle assessments, several guidance documents have emerged recently from the Global CO_2 Initiative, the National Energy Technology Laboratory, and the National Renewable Energy Laboratory that further define assessment specifications for carbon capture and utilization. Overall agreement in the approaches is noted with differences largely based on the intended use cases. However, further guidance is needed for assessments of early stage technologies, reporting details, and guidance for policymakers and non-technical decision makers.

1. **Introduction**

Atmospheric carbon dioxide levels continue to increase and contribute substantially to climate change. The Paris Agreement and subsequent Intergovernmental Panel on Climate Change (IPCC) reports clearly lay out the urgent need to not only curb and reduce further CO_2 emissions but also call for removal of CO_2 from the atmosphere. The capacity of the atmosphere to store CO_2 before catastrophic consequences would result is finite [1] and action is needed now. Along with other approaches to furthering the critically needed reduction of atmospheric CO_2 levels, such as de-fossilization of energy systems, underground CO_2 storage, and reforestation, new strategies for treating waste CO_2 are increasingly needed. Among the most promising of these are carbon capture and utilization (CCU) technologies, which incorporate processes to transform waste carbon dioxide into useful products available for purchase by global commercial entities and private citizens [2], [3], [4], [5]. There is also a complementary effort to inform and increase the practice of agriculture that sequesters CO_2 in soils. While sequestration of carbon in geologic reservoirs contributes to CO_2 removal efforts, economic value can only be achieved for Enhanced Oil Recovery (EOR). Thus, the need 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 energy such as wind and solar, and other emissions reduction efforts [2], [6]. Like these, CCU technologies address the urgent need for action to counter negative effects of climate change. In response to the challenges and opportunities presented by this need, new technologies and systems for CO_2 capture, conversion, and utilization for sustainable products, which enable a circular carbon economy, are being explored in an increasing number of research and production projects around the world [7], [8], [9], [10], [11], [12].

In this context, assessment of new CCU technologies is essential for accurate evaluation and prediction of their environmental and economic benefits and risks. Life cycle assessment (LCA) and techno-economic assessment (TEA) are tools that can provide this information and guide R&D efforts as well as policy development and decisions about which technologies merit commercializing into the marketplace [13].

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 [14], [15], [16]. 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, assumed different regional locations, were performed with varying methods, or employed methods that are either too generic or were defined for other product categories [17], [18].

CO_2 utilization is a new actor on the global stage, and those who are leading its development must ensure that a common language, guidelines, and set of technology evaluation tools be available for use by companies, researchers, and policymakers working in this emerging space. Life cycle assessment procedures are actually described and defined in two generic ISO standards (ISO 14040 and 14044). However, the application to CCU is rather new and a variety of approaches has been developed and is in use. Emerging from this variety is a need for harmonization of procedures for LCA and TEA for CCU and for consistent interpretation and reporting of the results. In this context, guidelines have been published recently that bridge between generic standards and program-specific guidance [15]. Additional detailed guidance was provided for specialized CCU cases [19], [20], [21]. It must be noted that other organizations as well as companies are working on assessment guidelines. An example is the work done by the Joint Research Centre (JRC) for the European Commission. Academy, industry, policy, and civil society experts working in the carbon dioxide capture and utilization space need to jointly explore and develop CO_2 metrics, best practices, validation, and the need for further action. Ideally, a harmonized global toolkit will be available 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. A common ground is important as for example illustrated in another global effort by the work of the Task Force on Climate-related Financial Disclosures, seeking to "develop recommendations for voluntary climate-related financial disclosures that are consistent, comparable, reliable, clear, and efficient, and provide decision-useful information to lenders, insurers, and investors" (https://www.fsb-tcfd.org/). The payoff for these efforts is clear: comprehensive, consistent, and transparent LCAs/TEAs and reporting of their results will facilitate funding decisions and promote sustainability-driven technology development. In fact, this is of course the case not only for CCU technologies but any new technologies.

2. Status of guideline harmonization

The Global CO_2 Initiative and the National Energy Technology Laboratory (NETL) have completed initial versions of guidance documents intended to advise on the execution of TEAs and LCAs for CCU projects [15], [22]. 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 the National Renewable Energy Laboratory (NREL) have developed best practices for TEA of CCU technologies but have not yet formalized these recommendations in a specific guidance document [22], [23].

2.1 LCA Guidance Documents

LCA guidance documents by the Global CO_2 Initiative and NETL 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 Utilization Program, i.e., the specification of coal-fired power plants as the source of CO_2. In addition to following International Organization for Standardization (ISO) standards, both documents (1) favor system expansion as a co-product management method, (2) require that the source of the CO_2 be included in the system boundary, (3) acknowledge that the primary research question will likely involve the comparison of a CCU system and a reference system, (4) use similar classifications for technology readiness levels (TRLs), and (5) assign a multi-product functional unit based on technical equivalency. This shows that increasing specialization in terms of application, use case, or end user need leads to guidelines that are applicable only when respective conditions are met but are otherwise in full compliance with overarching standards or guidelines as depicted in Figure 1.

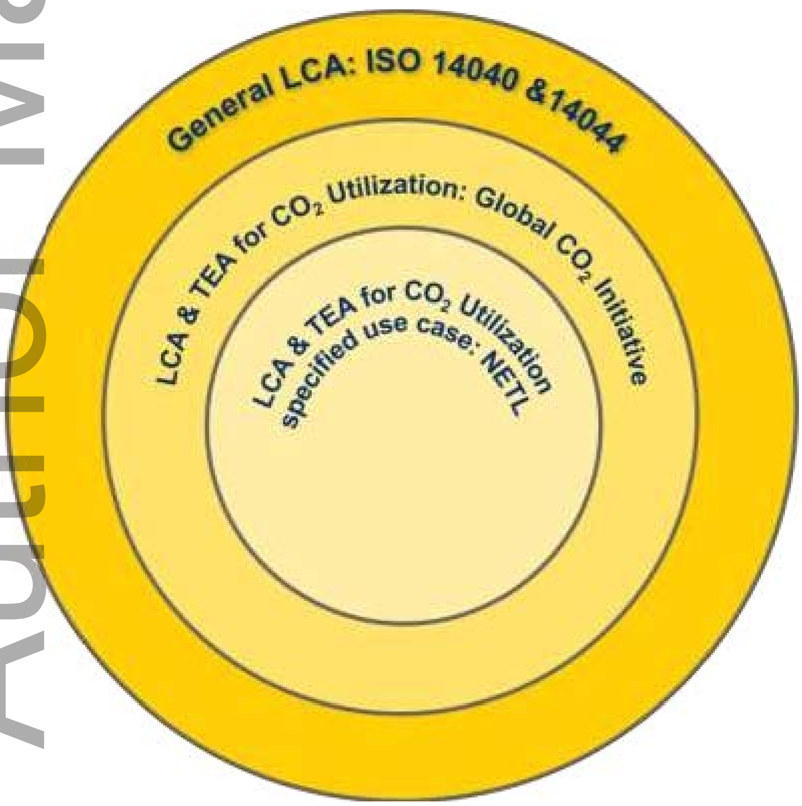

Figure 1: Illustration of how guidance for LCAs can be subsets of each other, fully in compliance, yet more specialized the more the use case is specified. The overarching ISO

standard for life cycle assessment provides the framework for the guidelines for LCA of general CO_2 utilization published by the Global CO_2 Initiative (GCI). The guidelines by NETL further specialize by specifying the source of CO_2.

The documents differ primarily in their suggested data sources for impact assessment and inventory. The Global CO_2 Initiative suggests the tools from the Institute of Environmental Sciences (CML) at the University of Leiden for global applications and Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) v2.0 for U.S. applications [24]. The Global CO_2 Initiative also includes standardized scenarios for CML results: status-quo, low decarbonization, high decarbonization, and full decarbonization. NETL guidance is exclusively U.S.-based and requires TRACI v2.1 [25]. 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.

2.2 **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. Through a recent workshop, TEA practitioners from the Global CO_2 Initiative, NREL, and NETL discussed and compared their respective TEA methodologies for CCU technologies and determined that they are generally consistent with each other.

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 [22]; these can be incorporated into TEA for CO_2 utilization.

Both NREL and NETL provide TEA guidance for early-stage development technologies 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. 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.

The standard TEA methodology used by NREL employs five classes of analysis strategies [26] that 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 performance of TEA over a range of TRLs requires the application of different analysis strategies 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. In contrast to that, TEA of high-TRL technologies uses more rigorous process designs and economic evaluations. In these cases, it is imperative that the

TEA team works 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 TEAs.

3. The Need for Streamlined LCAs and TEAs for Low-TRL Projects

Research funders, investors, corporations, and policymakers are interested in evaluating the merit and potential of new technologies as early as possible. However, the assessment and evaluation of low-TRL CCU projects pose particular difficulties. Conventional LCA and TEA methods require large amounts of data and substantial time and effort. Such data are 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 suitability for commercialization must be made. There is a need for "streamlined" assessments that would enable reasonably certain assessment results with less effort in general and for technologies at an early stage in their technological maturity [27]. 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 [28].

At present, such methods, though nominally available, are of unsatisfactory quality for providing reliable decision support. 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 [29].

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 [30]. 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.

4. The Need for Guidelines for Successful Interpretation of LCA and 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 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. Thus, a need exists 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 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 that (1) the system boundaries are complete and include the source of CO_2 for the utilization project and (2) multifunctionality is an inherent characteristic of CCU systems, which requires thoughtful development of comparison/benchmark systems to assess potential benefits.

It is noted 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. Thus, guidance for the interpretation of TEA would benefit the community by heading off common pitfalls and miscommunications. It is critical to the development of guidelines for successful interpretation of TEA results that (1) generally accepted approaches, i.e., frameworks or methodologies for TEA are defined, (2) TEA is differentiated from business cases as the two have different intended uses, (3) the class/stage of the TEA analysis is defined and provided, e.g., hot-spot analysis for low- TRL technologies versus in-depth process design and cost determination for high-TRL technologies. The classification of a TEA into one of the five 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. Further, it is necessary to (4) harmonize the nomenclature across various TEA guidelines, existing and emerging, (5) ensure that guidelines for interpretation take international perspectives and needs into consideration, such as differences in taxation laws, (6) define broadly-applicable approaches and methods for linking TEA and LCA through common metrics, especially for highlighting direct and indirect relationships such as trade-offs, (7) provide scenario and sensitivity analyses to avoid the pitfall of focusing too much on singular cost values, i.e., the inherent value of TEA lies not in the exact cost output, but in the insight provided into the key cost drivers, and (8) analyze and report uncertainty in cost estimates, especially for low-TRL technologies and unit operations that have not yet been commercialized.

Furthermore, since emerging CCU technologies must be evaluated on environmental and economic performance, an integrating approach for LCA and TEA is needed. This could follow a preliminary methodological basis that can be leveraged and extended to CCU technologies [31]. Integrating LCA and TEA offers multiple advantages over separate TEA and LCA evaluations. (1) A combined LCA and TEA based approach will help determine emerging CCU technologies that are both economically *and* environmentally promising. This approach can help deprioritize CCU technology alternatives, which are only promising in a single dimension, economic or environmental. For example, while TEA studies show that CCU methanol may be economically viable [32], corresponding LCA studies demonstrate that CCU methanol is environmentally sub-optimal [33], [34]. (2) The opportunity to leverage material and energy inventory data requirements, which forms the basis for both an economic and environmental assessment, makes an integrated LCA and TEA approach better suited to resolve challenges that are unique to either LCA or TEA. For example, the issue of data confidentiality is widely prevalent in TEA as costing information may not be not publicly available and propriety to commercial entities or industry members developing the CCU technology. In such a scenario, an integrated approach can develop reasonable estimates of costs based on the life cycle inventory data, which was used for the LCA. (3) An integrated LCA and TEA approach can prospectively identify critical CCU technology parameters and hotspots, which can produce the most significant environmental *and* economic benefits upon improvement through future R&D. (4) An integrated approach helps monetize and incorporate the costs of externalities and environmental burdens, that are by quantified by the LCA, as a part of the overall life cycle economic cost of a CCU technology [31]. (5) The characterization of uncertainty for both environmental and economic performance across technology readiness levels (TRLs) can draw on the same uncertainty estimates for input parameters that are in common to both analyses.

5. **Communicating LCA and 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.

Furthermore, guidance is needed to help commissioners of studies and decision-makers determine necessary aspects for the scope of the study to ensure that outcomes are relevant, interpret the study, and make qualified statements from quantified outputs. This guidance is vital, because often practitioners who conduct the LCAs and TEAs are not the decision-makers who 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. We recommend the creation of a standardized, globally applicable vocabulary/nomenclature for carbon utilization studies.

6. Putting Results in Context for "Go/No-Go" Decisions

The goal, scope, system boundary, energy and material inventories, and technological parameters provide the context in which an LCA or TEA is conducted for CCU technologies. Clear reporting of the context of TEAs and LCAs 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., if carbon negative deployment is contingent upon the 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 ("power to X technologies") should account for the economic or environmental opportunity cost of that renewable energy being used for CCU versus being supplied to the grid or used in competing technologies to offset CO_2 emissions from fossil electricity.

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 also necessary. Uncertainties in the material and energy inventories 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 uncertainty 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/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 provide opportunities to conduct environmental and economic breakeven analyses under different technology improvement pathways, identify strategies to shorten breakeven periods, and construct economically and environmentally sustainable pathways for commercialization of the CCU technology [35], [36]. 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.

7. **Conclusions**

The use of carbon dioxide as a feedstock for a broad range of products can help mitigate the effects of climate change by reducing atmospheric CO_2 levels through long-term removal of carbon or as part of a circular carbon economy. Research on capture and conversion technologies has intensified in recent years and the interest in deploying these technologies is growing fast. However, a sound understanding of the environmental and economic impact of these technologies is required to drive fast deployment and avoid unintended consequences. Life cycle assessments and techno-economic assessments are useful tools to quantify environmental and economic metrics; however, these tools can be very flexible in how they are applied, with the potential to produce significantly different results depending on how the boundaries and assumptions are defined. Built on ISO standards for generic life cycle assessments, several guidance documents have emerged recently from the Global CO_2 Initiative, the National Energy Technology Laboratory, and the National Renewable Energy Laboratory that further define assessment specifications for carbon capture and utilization. Overall agreement in the approaches is noted with differences largely based on the intended use cases. Key requirements and needs for further guidance are identified, especially for assessments of early stage technologies, reporting details, and guidance for policymakers and non-technical decision makers.

Carbon capture and utilization technologies represent a global opportunity albeit with some local differences. Thus, researchers who are developing methods for LCA and TEA must take further international perspectives into account to incorporate a wider global perspective in order to have the highest impact possible. Further efforts to harmonize across what has already been attempted and achieved will be valuable for the evolution of the methods. 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. The payoff for these efforts would be comprehensive, consistent, and transparent LCAs/TEAs and reporting of their results will facilitate funding decisions and promote sustainability-driven technology development. Beyond carbon capture and utilization the same effort for harmonized assessment methods could benefit the development and deployment of any new technology.

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References

[1] J. Rogelj, P. M. Forster, E. Kriegler, C. J. Smith, R. Seferian, *Nature* **2019**, *571*, 335-342.

[2] E. National Academies of Sciences, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, National Academies Press, Washington (DC), **2018**.

[3] P. Styring, E. A. Quadrelli, K. Armstrong, Elsevier, **2015**, p. 336.

[4] S. J. Friedmann, *Frontiers in Climate* **2019**, *1*.

[5] CO_2 Sciences, Global CO_2 Initiative, University of Michigan, Ann Arbor, MI, USA, **2016**, https://deepblue.lib.umich.edu/handle/2027.42/150624

[6] P. De Luna, C. Hahn, D. Higgins, S. A. Jaffer, T. F. Jaramillo, E. H. Sargent, *Science* **2019**, *364*.

[7] A. Kätelhön, R. Meys, S. Deutz, S. Suh, A. Bardow, *Proc Natl Acad Sci USA* **2019**, *116*, 11187-11194.

[8] M. Aresta, A. Dibenedetto, A. Angelini, *Journal of CO2 Utilization* **2013**, *s 3–4*, 65–73.

[9] D. Zhang, Z. Ghouleh, Y. Shao, *Journal of CO2 Utilization* **2017**, *21*, 119-131.

[10] R. S. Norhasyima, T. M. I. Mahlia, *Journal of CO2 Utilization* **2018**, *26*, 323-335.

[11] R. M. Cuéllar-Franca, A. Azapagic, *Journal of CO2 Utilization* **2015**, *9*, 82-102.

[12] P. R. Yaashikaa, P. Senthil Kumar, S. J. Varjani, A. Saravanan, *Journal of CO2 Utilization* **2019**, *33*, 131-147.

[13] J. Artz, T. E. Müller, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow, W. Leitner, *Chemical Reviews* **2018**, *118*, 434-504.

[14] DOE, Office of Project Management Oversight & Assessments, US Department of Energy, , **2011**, https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1

[15] A. Zimmermann, J. Wunderlich, G. Buchner, L. Müller, K. Armstrong, S. Michailos, A. Marxen, H. Naims, F. Mason, G. Stokes, E. Williams, Global CO_2 Initiative, University of Michigan, Ann Arbor, MI, USA, **2018**, 10.3998/2027.42/145436

[16] G. A. Buchner, A. W. Zimmermann, A. E. Hohgräve, R. Schomäcker, *Industrial & Engineering Chemistry Research* **2018**, *57*, 8502-8517.

[17] M. Pérez-Fortes, J. C. Schöneberger, A. Boulamanti, E. Tzimas, *Applied Energy* **2016**, *161*, 718-732.

[18] D. S. Kourkoumpas, E. Papadimou, K. Atsonios, S. Karellas, P. Grammelis, E. Kakaras, *International Journal of Hydrogen Energy* **2016**, *41*, 16674-16687.

[19] S. Michailos, P. Sanderson, A. V. Zaragoza, S. McCord, K. Armstrong, P. Styring, Global CO_2 Initiative, University of Michigan, Ann Arbor, MI, USA, **2018**, 10.3998/2027.42/145723

[20] S. McCord, A. Villa Zaragoza, P. Sanderson, K. Armstrong, P. Styring, C. Hills, P. Carey, M. Osbourne, L. Müller, A. Bardow, Global CO_2 Initiative, University of Michigan, Ann Arbor, MI, USA, **2018**, 10.3998/2027.42/147467

[21] A. Zimmermann, R. Schomäcker, E. Gençer, F. O'Sullivan, K. Armstrong, P. Styring, S. Michailos, Global CO_2 Initiative, University of Michigan, Ann Arbor, MI, USA, **2019**, 10.3998/2027.42/147468

[22] NETL, US Department of Energy, National Energy Technology Laboratory, **2019**, https://www.netl.doe.gov/LCA

[23] NREL, US Department of Energy, National Renewable Energy Laboratory, **2019**, https://www.nrel.gov/analysis/techno-economic.html

[24] J. C. Bare, *Journal of Industrial Ecology* **2002**, *6*, 49–78.

[25] J. C. Bare, G. A. Norris, D. W. Pennington, T. McKone, *Journal of Industrial Ecology* **2003**, *6*, 49-78.
[26] AACEI, **2019**, http://library.aacei.org/pgd01/pgd01.shtml
[27] R. Song, A. A. Keller, S. Suh, *Environmental Science & Technology* **2017**, *51*, 10777-10785.
[28] B. Subramaniam, R. K. Helling, C. J. Bode, *ACS Sustainable Chem. Eng.* **2016**, *4*, 5859-5865.
[29] B. A. Wender, R. W. Foley, V. Prado-Lopez, D. Ravikumar, D. A. Eisenberg, T. A. Hottle, J. Sadowski, W. P. Flanagan, A. Fisher, L. Laurin, M. E. Bates, I. Linkov, T. P. Seager, M. P. Fraser, D. H. Guston, *Environ. Sci. Technol.* **2014**, *48*, 10531–10538.
[30] D. Ravikumar, T. P. Seager, S. Cucurachi, V. Prado, C. Mutel, *Environmental Science & Technology* **2018**, *52*, 6534-6543.
[31] A. Kendall, G. A. Keoleian, G. E. Helfand, *Journal of Infrastructure Systems* **2008**, *14*, 214-222.
[32] S. Szima, C. C.-C. Cormos, *Journal of CO2 Utilization* **2018**, *24*, 555-563.
[33] J. C. Abanades, E. S. Rubin, M. Mazzotti, H. J. Herzog, *Energy & Environmental Science* **2017**, *10*, 2491-2499.
[34] D. Ravikumar, G. Keoleian, S. Miller, *Environmental Science & Technology* **2019**, *in review*.
[35] S. Michailos, S. McCord, V. Sick, G. Stokes, P. Styring, *Energy Conversion and Management* **2019**, *184*, 262-276.
[36] H. A. Daggash, C. F. Patzschke, C. F. Heuberger, L. Zhu, K. Hellgardt, P. S. Fennell, A. N. Bhave, A. Bardow, N. Mac Dowell, *Sustainable Energy & Fuels* **2018**, *2*, 1153-1169.

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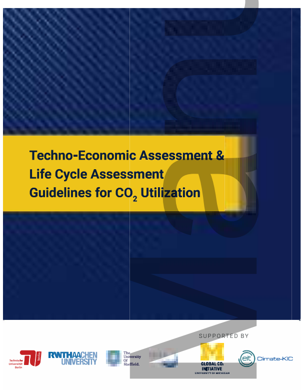
Carbon dioxide utilization technologies can help mitigate the effects of climate change. However, the environmental and economic impact must be assessed to drive fast deployment and avoid unintended consequences. Life cycle assessments and techno-economic assessments are useful but complex tools for this purpose. This work describes efforts to develop harmonized international guidance to allow transparent and fully comparable evaluations.

ToC figure: Either use Figure 1 from this manuscript or for a more colorful image use the cover page of the Guidelines from the Global CO_2 Initiative but that would not represent the breadth of what is described in the paper, only a subset.



ToC keyword: carbon dioxide capture, utilization and storage