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AssessCCUS: An Integrated Approach for Aggregating Resources to Enable Techno-Economic and Life Cycle Assessment of Carbon Management Technologies

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INTRODUCTION

Carbon capture, utilization, and storage (CCUS)—also sometimes known as carbon management—technologies are becoming an increasingly important part of the portfolio of technologies necessary to mitigate climate change and defossilize industrial production systems (Sick, 2021). These technologies capture carbon dioxide from industrial point sources or from the atmosphere directly and then either sequester it or use it as a carbon source in valuable products. Potential utilization pathways include, but are not limited to, concrete, fuels, and certain commodity chemicals, and sequestration pathways can include permanent geological storage or temporary storage in natural sinks ranging from forests to agricultural soil. Regardless of the pathway, assessment of the economic and environmental performance of the technologies is important for understanding their potential scalability and impact as well as developing plans to minimize life cycle costs and potential environmental trade-offs. A full discussion of potential trade-offs associated with CCUS is outside the scope of this article, but promoting assessment broadly helps to stimulate important conversations about the benefits and drawbacks of any particular technological choice.

Consistent environmental assessment is also required for consistent low-carbon policy implementation, as a common understanding of the benefits and challenges of particular technologies helps craft meaningful regulations. Corporate actors also prefer consistent methodologies and policies to reduce confusion, redundancy, and wasted time and effort. Life cycle assessment (LCA) and techno-economic assessment (TEA) are environmental and economic assessment methodologies that can fulfill these purposes. LCA is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006) while TEA is defined as a method that "[provides] information on the economics of a given [process] or [product] associated with a specific location and time period, along with their accuracy and variability over time due to technological developments or future [scenario] conditions"[1].

While LCA and TEA can be performed for any kind of industrial process and there has been a significant amount of work done on developing general guidance for both methodologies (ISO, 2006; AACE International, 2021), customized guidelines are useful for CCUS technologies to

[1] https://assessccus.globalco2initiative.org/glossaries/

help address common pitfalls and enable "apples-to-apples" comparisons (Zimmermann et al., 2021). Various organizations have created LCA and TEA guidance with a specific focus on CCUS technologies (Skone et al., 2019; Zimmermann et al., 2020; Roussanaly et al., 2021), and harmonization among these guidelines is important to enable comparable and consistent assessments of established and emerging technologies (Sick et al., 2020). The authors recommend reviewing these references for a comprehensive overview of recommendations for and features of life cycle and techno-economic assessment of CCUS technologies.

The International Carbon Capture and Utilization Assessment Harmonization Group emerged in 2020 to harmonize related efforts on the part of many different organizations. This group consists of experts from research institutions and organizations from both North America and Europe including the Global CO_2 Initiative at the University of Michigan, the National Energy Technology Laboratory, the National Renewable Energy Laboratory, Argonne National Laboratory, National Research Council Canada, IASS Potsdam, TU Berlin, RWTH Aachen, the University of Sheffield, and EIT Climate-KIC. Representatives from each organization joined task teams to work on topics relevant to LCA and TEA, and the group held a series of corresponding webinars in May 2021[2]. Topics for the teams ranged from integration of LCA and TEA results to technology learning curves, and the results of the team focused on the AssessCCUS website[3] are discussed in this article.

AssessCCUS was funded by the U.S. Department of Energy, and the Global CO_2 Initiative led the implementation of the project with support from others in the International CCU[4] Assessment Harmonization Group. The project was initiated in response to the perceived need for global resource centralization for LCA and TEA of CCUS technologies. There are many different articles, reports, guidance documents, tools, videos, databases, and other resources related to LCA and TEA of these technologies, but many of these may be difficult to find, especially for those new to the field, or may only focus on a single topic. For example, the National Energy Technology Laboratory already offers a hub for CCU LCA resources[5]. AssessCCUS refers frequently to this resource but also integrates resources from many other places and focuses on TEA in addition to LCA. Centralizing as many existing resources as possible expedites the discovery process and allows for rapid, centralized access.

AssessCCUS also features high-level descriptions of carbon capture, utilization, and storage along with LCA and TEA to help communicate these concepts in clear terms to general audiences. In addition to these descriptions, the site features the glossary[6] created by the nomenclature team of the International CCU Assessment Harmonization Group. While harmonized definitions of terms and phrases are useful to practitioners, they can also aid the public in understanding arcane, complicated, or contested concepts, such as "carbon rainbow," "renewable carbon," and "system expansion." In general, the site attempts to meet the needs of diverse audiences—ranging from practitioners to students to entrepreneurs—by offering a diverse selection of resources.

This article describes how AssessCCUS came to be and the impact that this project and similar ones could have over time. The following section describes an initial stakeholder needs assessment exercise that informed the project along with the process for selecting resources to be included on the site. After this, the next section offers some insight on visitor statistics so far as well as some actual use cases for the site. A call to action is then provided for the assessment and CCUS community to create related resources, such as online courses and new databases, to advance assessment and ultimately deployment. The article concludes with some discussion of limitations of and opportunities for this work.

METHODS FOR DATA COLLECTION

Audience Mapping

The primary goal of AssessCCUS is to offer a repository that provides useful and, more importantly, usable information for a variety of audiences. To accomplish this, one of the first steps was conducting a user persona exercise, which was provided by the National Renewable Energy Laboratory. The framework for this exercise is provided in the **Supplementary Material** of this article. The team began by mapping the potential audiences of an online repository of resources related to LCA and TEA of CCUS technologies along with their assumed objectives and needs. Identified audiences included researchers/professors, students, entrepreneurs, corporate managers, investors, policymakers, funding agencies, LCA/TEA practitioners, journalists, and the general public. **Table 1** shows the results of this mapping process.

The assumed needs for each group directly influenced the structure of the site along with the resources that were ultimately included. **Figure 1** shows the sitemap of the AssessCCUS website at the time of writing in November 2021. The LCA and TEA sections of the website were separated as the working group decided that most visitors would be looking for resources related to one methodology or the other. The specific content included on each page can be reviewed directly on the AssessCCUS site (see text footnote 3).

While individuals from any of the audiences could conceivably benefit from AssessCCUS, there were a few groups that were prioritized during development based on the pillars of the Global CO_2 Initiative, which are education, research, and evaluation. Offering high-level explanations and definitions of phrases relevant to CCUS, LCA, and TEA will primarily help students and the public educate themselves about this important space. The templates, instructional videos,

[2]https://www.youtube.com/playlist?list=PL71vVXxHPbEmm9-EYU5SK_N5hr6IIR3CB

[3]https://assessccus.globalco2initiative.org/

[4]The initialism "CCU" stands for "carbon capture and utilization" and is similar to CCUS but focuses solely on the capture of carbon dioxide and subsequent utilization to manufacture valuable products. CCU excludes considerations of permanent storage or sequestration that do not result in valuable, tangible products.

[5]https://netl.doe.gov/LCA/CO2U

[6]https://assessccus.globalco2initiative.org/glossaries/

TABLE 1 | Results of audience needs mapping.

Audience group	Example	Assumed objectives	Assumed needs
Researchers/professors	Chemical engineer developing new process	Funding, discovery, development, publishing	LCA/TEA guidance, templates, databases, case studies
Students	Engineering student working as research assistant	Learning, contributing to research	Overviews, glossaries, video walkthroughs
Entrepreneurs	Carbon removal startup founder	Funding, marketing, improving product, complying with regulations	Templates, video walkthroughs, overviews, databases
Corporate managers	Chemical company research manager	Assessing products, improving profitability or marketability	Overviews, templates (for practitioners), information about new processes
Investors	Cleantech venture capital investment associate	Sourcing new investments, conducting due diligence, learning	Overviews, templates, information about new processes
Policymakers	State senator working on green procurement policy	Passing legislation, learning	Overviews (especially of LCA)
Funding agencies	U.S. Department of Energy program manager	Awarding funding, ensuring regulatory compliance	Overviews, templates
LCA/TEA practitioners	LCA consultant	Performing sound analyses	Templates, video walkthroughs, databases
Journalists	Climate change newsletter author	Publishing interesting content	Overviews, glossaries
General public	Member of public without knowledge of CCUS	Learning, improving purchasing decisions	Overviews, glossaries

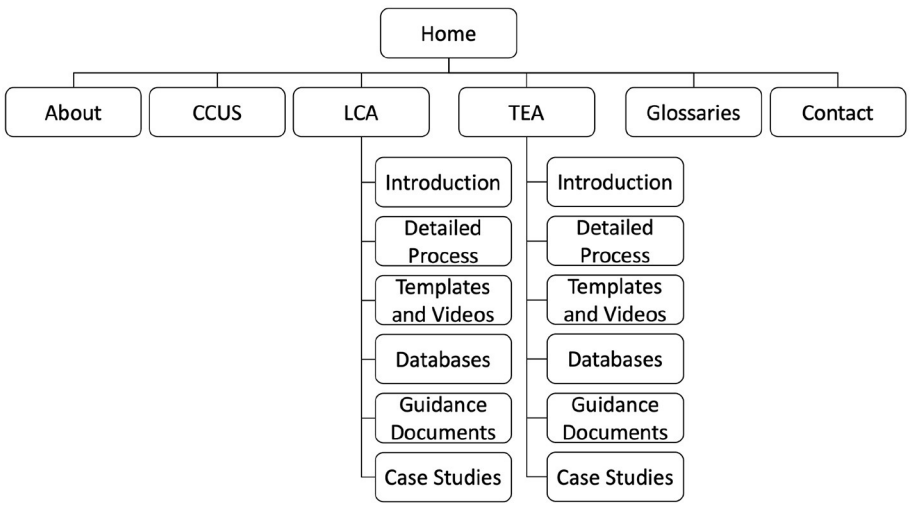

FIGURE 1 | AssessCCUS sitemap demonstrating hierarchy of pages featured on the website.

and detailed process descriptions will enable evaluation on the part of entrepreneurs who are often looking to apply these methodologies to evaluate early-stage technologies. Finally, the databases, guidance documents, and case studies could be helpful for enabling LCA/TEA research on the part of practitioners of these methodologies.

Resource Selection

To meet the needs of its anticipated users, AssessCCUS contains explanations, reports, templates, videos, databases, guidance documents, case studies, and glossaries. A complete list of the resources on the site as of November 2021 are listed in the **Supplementary Material** of this article. These resources were gathered through various means. The first step involved listing resources offered by organizations in the International CCU Assessment Harmonization Working Group, such as guidance documents from the National Energy Technology Laboratory (Skone et al., 2019) and the Global CO_2 Initiative (Zimmermann et al., 2020) as well as Argonne National Laboratory's GREET model[7]. The second phase involved soliciting specific resources from members of the team devoted to working on AssessCCUS including ones that team members use regularly when conducting LCA and TEA. This step resulted in

[7]https://greet.es.anl.gov/

the inclusion of resources such as Alibaba[8] and a study on carbon capture costs by Budinis et al. (2018). Phase three involved an internet search for such resources using terms such as "life cycle assessment database," "cost modeling templates," and "capital equipment cost data." These searches yielded resources such as the Life Cycle Initiative's map of LCA databases[9] and Appendix D from *Rules of Thumb in Engineering Practice* (Woods, 2007). The fourth phase involved soliciting recommendations from the audience of the webinar presentation[10] for AssessCCUS, leading to the inclusion of resources including GHGenius[11]. The final phase of resource collection is ongoing, as those visiting the site are encouraged to submit recommendations for new resources on the website's *Contact* page[12]. This final step is inspired by general open-source and crowdsourcing approaches and will ideally result in an increasingly useful and impactful repository over time.

Certain resources on AssessCCUS were created specifically for the site. Informational sections were drafted using background knowledge of those in the working group and existing resources from the Global CO_2 Initiative. The *Detailed Process* pages are based entirely on the Initiative's Techno-Economic Assessment and Life Cycle Assessment Guidelines for CO_2 Utilization (Version 1.1) (Zimmermann et al., 2020). The templates, template walkthrough videos, and the custom glossary were all created by members of the International CCU Assessment Harmonization Group for the site. The generic LCA and TEA templates created for AssessCCUS ultimately led to the creation of templates focused specifically on algae, aggregates, chemical synthesis, carbonated concrete, and direct air capture. These templates are provided on the site and are discussed in a separate publication (Faber et al., 2021).

VISITOR STATISTICS

At the time of writing this article in November 2021, AssessCCUS has had over 2,500 unique visitors and over 6,000 pageviews. However, the total number of people who could benefit from this site likely numbers in the tens if not hundreds of thousands, meaning that these kinds of tools need to be accessed by a number of individuals that is orders of magnitude higher than the current level. Significant promotional effort may be required to achieve this, and over time translations and regional customization may be required to help audiences from diverse geographies to access and utilize the material on the site. As a website, AssessCCUS can only be accessed virtually, and based on statistics provided by the site's hosting service, many discover AssessCCUS through Google searches for related concepts or the Wikipedia page for techno-economic assessment.

The most popular pages besides the *Home* page are the top-level *CCUS*, *TEA*, *LCA*, and *About* pages, which is unsurprising as they are the other pages that are immediately visible upon viewing the *Home* page. After these pages, the *Detailed Process* and *Databases* pages in the LCA section of the site along with both *Templates and Videos* pages have the most visitors. While inferring too much from this data may not be prudent, it may suggest that users are particularly interested in LCA resources along with general templates for conducting assessments, implying that more work in these areas could be particularly valuable to the community.

To the knowledge of the authors, AssessCCUS has been used on four separate occasions as part of LCA and TEA training exercises. Startups in the AirMiners Launchpad[13] used resources on the site to learn about TEA and create preliminary models as part of two separate workshops, and startups in the Carbon to Value Initiative[14] used the website in a similar way before a lecture on LCA. The site was also presented to PhD students in a university laboratory to serve as a resource for conducting LCA and TEA. These startups and individuals will ideally continue to use AssessCCUS for their LCA and TEA needs as well as refer others to the site if they can find value in these resources as well.

CALL TO ACTION

While the resources provided by AssessCCUS are applicable for a variety of applications, there are many others that would be beneficial for meeting the needs of the site's intended audiences. Assessment efforts and related resources need to be global given the international nature of both climate change and technology development. Such resources also need to be as accessible as possible, which may involve offering existing resources in different languages, making them open access, or tailoring them to particular regions. Creating a useful *and* usable set of resources to enable consistent assessment of carbon management technologies around the world is a difficult task and requires effort on the part of many people and organizations. What follows is a list of ideas that could be pursued to further advance this work.

One example is online training modules or online courses, possibly in the form of massive open online courses (MOOCs). LCA and TEA are often taught as part of graduate-level engineering courses at universities, but many more people will require skill in these methodologies to enable more organizations to both study and understand the environmental and economic characteristics of new CCUS technologies. Depending on the structure of the courses, they could allow students located anywhere with internet to efficiently build comprehensive methodological knowledge, enhance skills through projects and practice problems, and collaborate and network with others. It would be especially useful if such courses could be offered in multiple languages and integrate relevant, regional information such as local regulations or types of CCUS technologies that may be more popular in certain parts of the world.

New and expanded databases could also be highly valuable, especially to LCA and TEA practitioners. Recent and reliable cost data for various materials and pieces of equipment is famously

[8]https://www.alibaba.com/
[9]https://www.lifecycleinitiative.org/applying-lca/lca-databases-map/
[10]https://www.youtube.com/watch?v=7ya8cjiUd1A
[11]https://www.ghgenius.ca/
[12]https://assessccus.globalco2initiative.org/contact/
[13]https://launchpad.airminers.org/
[14]https://www.c2vinitiative.com/

difficult to find, and vendors are often unwilling to share such information directly for research projects due to confidentiality concerns. For LCAs, more data on the environmental impacts of products, particularly esoteric ones, would be useful for increasing the accuracy of studies. Making such databases open source, well documented, international in scope, and easily accessible would all greatly increase their value to the community.

More demonstrative case studies of various CCUS pathways would also be valuable for both identifying potential economic and environmental hotspots of new technologies as well as demonstrating how LCA and TEA can be applied in a variety of situations. The Global CO_2 Initiative has already published a series of case studies (McCord et al., 2018, 2020; Michailos et al., 2018; Zimmermann et al., 2018; Zaragoza et al., 2020a,b; Wang and Schomäcker, 2021), but further examples of new technologies or deployments in locations other than the U.S. and Europe could provide significant value to both practitioners and those looking to learn more about new pathways or applying LCA and TEA methodology.

Explanations, templates, guidance documents, and case studies for other types of LCA and TEA methodologies could also be useful to the community. The integration of environmental and economic indicators is not covered on AssessCCUS but poses an important challenge as discussed in the International CCU Assessment Harmonization Group's workshop on LCA and TEA integration[15]. Separately, dynamic, prospective, and consequential life cycle assessment can all be relevant to holistically and usefully assessing CCUS technologies, but these methods were not covered by the Global CO_2 Initiative's guidelines and thus were not explored on AssessCCUS. Online and easily accessible resources similar to AssessCCUS covering these topics could be extraordinarily beneficial given their complexity and sometimes esoteric nature.

An online catalog of or forum for companies and individuals who practice LCA or TEA or specialize in particular CCUS technologies could also be quite useful. Those looking to learn more about a particular area of the CCUS or assessment spaces could benefit from finding relevant experts, and those looking to purchase assessment services would likely benefit from a convenient listing of relevant companies or consultants. This kind of site could become a "go to" resource for those looking to learn or hire someone to do an assessment or even for scholars looking to find collaborators and new ideas for studies.

Finally, an online tool that calculates manufacturing costs, emissions, and water use for products given user inputs is currently in production and will be featured on the AssessCCUS site by early 2022. This calculator will demonstrate the basic structure of inventory data collection, indicator calculation, and impact assessment, and it will allow users to download a spreadsheet with input data and corresponding calculations and visualizations. When combined with the databases and other resources on the site, it will help users complete their own LCAs and TEAs even more expediently and thus further expand the usefulness of AssessCCUS. Many audiences may be interested in deploying this calculator for their own projects, and some may even be interested in expanding on the idea. Possibilities for expansion include integration with existing databases or expanded uncertainty analysis.

There are likely many other ideas for creating assessment-enabling resources, and any of these could be featured on AssessCCUS or even integrated into the website. Ideally, the network of interlinked resources and people will continue to expand, allowing interested parties to more quickly find the resources they need from any entry point into the network. However, this network will always be a work in progress as technologies, databases, techniques, methodologies, and experts continue to emerge and change. AssessCCUS is only the first step, and the community is strongly encouraged to get involved and implement diverse approaches for enhancing global assessment efforts for carbon management technologies.

CONCLUSION

Many CCUS technologies are at low technology readiness levels and require consistent economic and environmental assessment for technologists and funders to efficiently improve performance and make go/no go decisions. Also, such assessments can help foster the acceptance of technology innovations as they enable non-experts to inform themselves about related ecological and economic implications. Carbon management technologies have also not received the same amount of attention from the general public and from policymakers as relatively more mature technologies such as solar photovoltaic systems and electric vehicles. AssessCCUS attempts to address these needs for awareness and methodological guidance by offering a centralized repository of resources necessary to learn about and conduct LCA and TEA for CCUS technologies. By providing simplified explanations, links to resources, templates, videos, databases, guidance documents, case studies, and glossaries, the site equips various audiences with the knowledge and tools necessary to learn about and conduct LCA and TEA.

However, AssessCCUS alone cannot satisfy the needs of all potential users, especially given the global need for this kind of assessment. Despite the existence of automatic translation tools, the site was written in English and links to resources geared toward English-speaking audiences. Resources will continue to be added over time, but there are likely many arcane ones that will simply never be found by those maintaining the website. Furthermore, while there are more unique visitors to the site with each passing day, it is highly unlikely that everyone who might ever need the site will be able to find it. Given these limitations, there is a great need for others—particularly those with translation capabilities and those with deep LCA and TEA experience—to help create and distribute resources to encourage broader adoption of both CCUS technologies as well as proper assessment methodologies. Other resources, such as online courses, new databases, case studies on emerging technologies, social media sites for practitioners and experts, and assessment calculators, would also be incredibly useful for educating interested parties and advancing the field. Everyone is

[15]https://www.youtube.com/watch?v=ppsxAgIU_iU

encouraged and invited to find and pursue unique and valuable ways to contribute to this effort.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

GF: conceptualization, writing–original draft, writing–review and editing, and visualization. CM: writing–review and editing. BO-K and JS: writing–original draft and writing–review and editing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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