Best Practices for Life Cycle Assessment (LCA) of Biomass Carbon Removal and Storage (BiCRS) Technologies

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Acknowledgements

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1. Introduction

Life Cycle Analysis/Assessment (LCA) is an existing framework that is well suited to evaluate the environmental implications of Carbon Dioxide Removal (CDR). By design, LCA provides a holistic perspective of the potential environmental impacts of a product or process across the different life cycle phases. This includes the extraction of raw materials through the end-of-life. Emissions to the environment (air, water, and land) are translated to a variety of potential impacts ranging from climate change to human health. Two International Organization for Standardization (ISO) standards provide the principles and framework (14040) and requirements and guidelines (14044) for conducting LCA (ISO 2006a, 2006b). A separate standard, ISO 14067, focuses specifically on the reporting of the carbon footprint for products (CFPs) (ISO 2018). It is largely based on ISO 14040/14044, but with a narrower focus on potential impacts related to climate change.

Not only can LCA be used to help determine the net CO_2e removal of a CDR approach, but it can also help with the assessment of potential tradeoffs with other environmental impacts. Even though the approaches for LCA are codified in the ISO standards, we recognize the need to establish specific best practices for the subjective elements in those standards to harmonize data and methods to allow for consistent assessments of CDR approaches. This document focuses specifically on one subset of CDR approaches, Biomass Carbon Removal and Storage (BiCRS).

1.1 Purpose

The U.S. Department of Energy (DOE) published best practices for LCA of direct air capture with storage (DACS) (Cooney 2022), a CDR technology that has gained significant interest. This is the second of a series of documents that aim to support robust accounting of full life cycle GHG emissions of CDR approaches. This document focuses on BiCRS technologies, a subset of CDR approaches that can provide decarbonization benefits via durable storage of carbon originated from biomass with or without producing energy or bioproducts that replace fossil carbon-derived counterparts. Robust and holistic LCA is critical for evaluating the potential for climate benefit and tracking the progress of BiCRS technologies. It also serves as the foundation for establishing equivalency for comparison across BiCRS technologies and, more broadly, other CDR approaches that facilitate uptake of BiCRS technologies in regulatory, market, and other settings.

The purpose of this effort is to provide specific best practices for implementing the ISO standards to BiCRS systems to enable consistent and robust LCAs across the four phases of LCA: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. We envision the audiences for this document to include technology developers, federal funding awardees, state- and federal-level policymakers and regulators, entities (companies, organizations, individuals) interested in evaluating BiCRS procurement, and potential host communities for BiCRS technologies.

While this document mentions examples of currently proposed pathways, it is not intended to be exclusively applicable to those pathways. The principles discussed could be generically applied to any engineered BiCRS system that provides the same function.

This is not a legal document and thus the recommendations included are provided as best practices based on the experience of the U.S. Department of Energy and its national laboratories. This document is not intended to qualify or disqualify any particular BiCRS pathway, but rather provide best practices for how LCAs of those approaches ought to be conducted in a robust and consistent manner.

DOE recognizes that the broader CDR landscape, inclusive of BiCRS, is in a period of rapid evolution in terms of scientific understanding, methods for robust monitoring, reporting, and verification (MRV), and market creation for commoditized credits. Those developments may result in modifications to Best Practices over time. This document is proposed as an initial proposal for applying LCA to BiCRS approaches. Additionally, as described in this document, some factors of LCA pertaining to biomass carbon accounting are individual to the type, location, and circumstance of the biomass being utilized, and require specific analytical considerations (e.g., spatial scales, temporal scales). Those considerations are only addressed in this document at a high level.

1.2 Goals and objectives

This document is envisioned as a complement to the ISO LCA standards (14040/14044) to address issues that are specific to applications of those standards to BiCRS analysis.

Goal 1: Foster consistency of LCA of BiCRS systems to enable more complete understanding of potential impacts across CDR strategies.

1.a Provide definition to key goal and scope elements in the LCA framework (functional unit, analysis scope, system boundaries, etc.).

1.b Include technical/physical flows as key outputs in addition to the LCA impacts to facilitate future updates and harmonization.

1.c Define the required elements for the life cycle inventory data collection.

1.d Recommend background data sources for the life cycle inventory data collection stage.

1.e Enable the assessment of a full suite of environmental impacts in addition to global warming.

Goal 2: Enable the assessment of sensitivity and uncertainty in results to provide confidence in the study outcomes and potential envelope of technology performance.

2.a Recommend best practices to conduct sensitivity and uncertainty analyses for BiCRS systems.

Goal 3: Leverage best practices from LCA research and the practitioner community to account for considerations specific to evaluation of technology improvement and deployment.

3.a Coordinate LCA efforts with TEA to the extent possible to allow for better understanding of potential operating envelope and corresponding impacts as the technology continues to improve.

3.b Suggest best practices unique to these applications that are not included in ISO 14040/14044.

The goals and objectives above provide the perspective from which this document was developed. It should be noted that this document is not a replacement for ISO 14040/14044 and does not do the following:

1. Instruct users exactly how to conduct and document an LCA – those requirements are well defined in the ISO 14040/14044 standards and other established LCA practices and guidelines.
2. Require the use of specific data sources and/or modeling platforms.
3. Provide a specific report template or reporting requirement.
4. Attempt to resolve legacy methodological issues that have been debated in the LCA research and practitioner community.

1.3 Document structure

This document is organized in chapters to introduce emerging BiCRS technologies, provide general LCA recommendations in accordance with all the life cycle stages of the ISO 14040/14044 framework, discuss unique LCA issues for BiCRS technologies, demonstrate LCA best practices for specific BiCRS technologies, and summarize best practice recommendations across all the LCA stages.

2. BiCRS technology categories

BiCRS technologies start with carbon drawdown via photosynthesis and storage via direct burial of the biomass or transformation of the biomass (e.g., via pyrolysis) and subsequent storage (e.g., via geologic injection) to achieve long-term biogenic carbon storage. The duration/durability of storage depends on several factors and is not represented by a single value, but rather a range for different BiCRS approaches. For the purposes of this document, 100-year durability is used as the starting point for consistency with the Carbon Negative Earthshot. A number of BiCRS technologies are being developed that use a wide variety of biomass, including but not limited to forest residues, agricultural residues, and urban waste, to store carbon in solid, liquid, or gaseous products derived from biomass. In these Best Practices, we categorize BiCRS technologies into dedicated BiCRS that focus on providing the carbon storage value and bioenergy with carbon capture and storage (BECCS), which provide both bioenergy and carbon storage values. While biomass-derived materials such as biochemical and bioproducts contain biogenic carbon that might be durably stored as part of the biomaterial during its designed service life, it is not discussed in the current scope of this document. Figure 1 presents the examples of BiCRS technologies in these two groups.

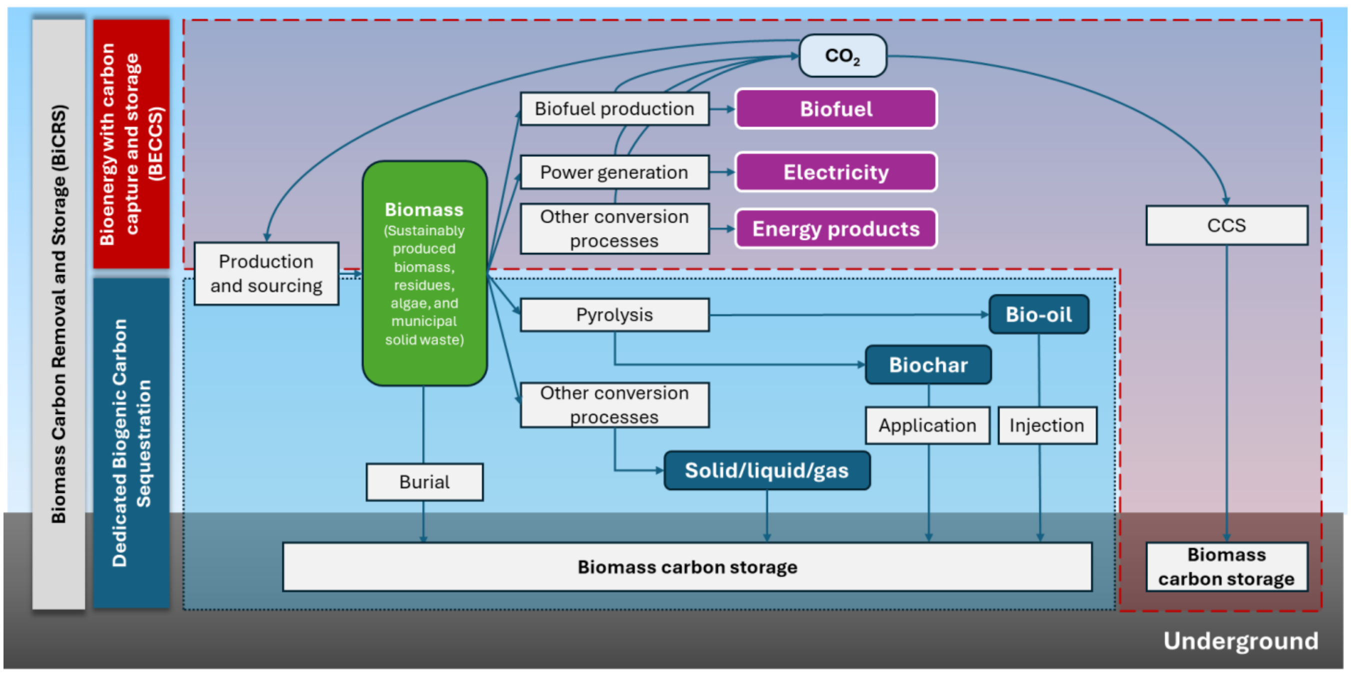


Figure 1. Biomass Carbon Removal and Storage (BiCRS) Technologies Encompassing Dedicated Biogenic Carbon Storage and Bioenergy with Carbon Capture and Storage (BECCS) Technologies. The Technology Pathways Depicted Here Are Examples.

2.1 Dedicated BiCRS technologies

The emphasis of these dedicated BiCRS technologies is on the value of the carbon content of biomass rather than on the energy content of biomass feedstock or bio-derived products. BiCRS uses biomass as a medium to remove CO_2 from the atmosphere and permanently sequester carbon in terrestrial storage or in long-lived bio-derived products (Sandalow et al. 2021). BiCRS technologies leverage the carbon storage capacity of biomass or bioproducts for durable carbon sequestration beyond their natural lifecycles when vegetation dies and decomposes and releases CO_2 back into the atmosphere. This section presents major examples of dedicated biogenic carbon sequestration technologies, namely, biomass burial, liquid injection, and stabilized biogenic carbon.

2.1.1 Biomass burial (biomass harvesting and storage)

Biomass burial stores or buries solid biomass (unprocessed or processed) to sequester carbon. Several versions of biomass burial structures have been proposed, ranging from fully aboveground burial mounds to fully underground mines and pits. Wood vault is an evolving biomass burial technology that uses specially engineered enclosures to store raw or minimally processed woody biomass deep underground, isolated from biologically active topsoil and thus creating anaerobic, dry, or cold conditions to prevent biomass from decomposition (Zeng and Hausmann 2022). It has advanced in several versions that use different storage methods in varied burial environment and could achieve a mega-tonne scale at a single vault (Zeng and Hausmann 2022).

To ensure durable storage, biomass feedstock may be processed through one or a combination of methods, including drying, salting, and the use of impermeable barriers to drastically reduce the decomposition rate of biomass or its derived products. There also has been research showing that direct burial of biomass in certain soils and climates can result in highly durable storage without advanced processing of the biomass (Zeng and Hausmann 2022).

2.1.2 Liquid injection

Biomass can be converted into liquids (e.g., bio-oil), with the carbon-rich liquids then injected into geological formations including reservoirs, saline aquifers, and caverns for durable storage. Fast pyrolysis, a thermochemical process, is one process that converts a range of biomass into bio-oil by rapidly heating biomass at temperatures typically ranging from 300°C to 600°C in the absence of oxygen. Properties of feedstock and conversion conditions are key factors that determine the quality and properties of bio-oil from fast pyrolysis. Note that char and gas are co-produced during fast pyrolysis (Fahmi et al. 2008).

Raw bio-oil from fast pyrolysis is unstable, and its characteristics may change over time, such as increased viscosity and phase separation (Venderbosch and Prins 2010). Because bio-oil typically has a pH range of 2–3 (Oasmaa et al. 2015), its acidic nature also makes it corrosive for equipment, trucks (e.g., tanks made of carbon steel), well castings, and rocks. To mitigate risks, some bio-oil’s properties may be modified prior to their transportation, injection, and storage.

By injecting bio-derived liquid underground, carbon is effectively removed from the atmospheric cycle, reducing net GHG emissions. Bio-liquid has properties that may enhance the stability of stored carbon, compared to gaseous CO_2 that can be prone to leakage. Bio-oil's higher viscosity and tendency for polymerization under pressure and temperature conditions within the reservoir can lead to a significant increase in its viscosity, effectively locking it in place and preventing leakage (Charm Industrial 2023), leading to more secure long-term storage.

2.1.3 Stabilized biogenic carbon (biochar)

Biogenic carbon can also be stored in long-lived products, which have the potential to carry a very stable form of carbon that significantly reduces biological (e.g., by fungi, bacteria) and thermal (by heat) degradation for extended time scales (hundreds to thousands of years). One promising long-lived product is biochar, a solid material obtained from the carbonization of biomass (Cha et al. 2016), which is produced from thermochemical conversion processes. Pyrolysis, hydrothermal carbonization, gasification, and torrefaction are some techniques to produce biochar (Yaashikaa et al. 2020), among which slow pyrolysis as the most commonly used to produce biochar. Slow pyrolysis carried out with longer residence time compared to fast pyrolysis typically yields more biochar than gaseous and liquid products under optimized conditions (Cai et al. 2020).

Biochar consists primarily of carbon, which ranges from approximately 50% to more than 80% by weight (Li and Tasnady 2023). Its high carbon content, along with the thermal stability and recalcitrant nature of biochar, makes it ideal for durable carbon storage. Biochar application offers numerous potential benefits for soil health and sustainable agricultural practices as well as for carbon sequestration. It is a challenge to quantitatively assess these co-benefits from a CDR perspective, which requires rigorous agronomic science, in-depth knowledge of ecological services, and advanced measurement techniques and are not discussed in this document.

Biochar is a heterogeneous mixture that consists of both aliphatic and aromatic organic compounds, exhibiting distinct permanence when applied to soil (Woolf et al. 2021). The recalcitrant carbon pools (with the larger aromatic structures) are reported to have a mean residence time in soil exceeding 1,000 years (Schmidt et al. 2022). On the other hand, the labile carbon pools, which typically contain aliphatic, small aromatic, and heteroaromatic carbon compounds, may degrade within the first several years of soil applications or last up to 100 years, depending on the chemistry of the compounds, soil type, and soil temperature, among others.

2.2 Bioenergy with carbon capture and storage (BECCS)

BECCS refers to a suite of technologies that seek to use biomass for dual purposes: usable energy production and carbon sequestration. BECCS has been among the most discussed CDR approaches in the literature over the past decade (Hilaire et al. 2019; Minx et al. 2017). Global BECCS potential corresponds to the order of 10 gigatonnes of CO_2 per year based on integrated assessment modeling (Fuhrman et al. 2023). BECCS has some unique features compared to other CDR technologies; while dedicated biogenic carbon sequestration requires energy inputs, BECCS can deliver energy outputs. To be categorized as BECCS, a system should produce energy alongside biogenic carbon storage over long periods of time (at least 100 years) (Appendix A1). Based on this definition, the International Energy Agency estimates that current worldwide BECCS capacity is around 2 million metric tons of CO_2/year (IEA 2024). If the projected CDR from BECCS projects in their early or advanced stages of deployment are considered, it could be summed to nearly 50 million metric tonnes CO_2 per year in 2023 (IEA 2024). Most of these projects are in the bioethanol sector, where high-purity CO_2 from the fermentation process is captured and stored. IEA Bioenergy reported operating and planned CCS projects including those from corn ethanol production such as Archer Daniels Midland (ADM), a corn ethanol company, presenting 1 million metric tons per year capture capacity in Illinois in co-located geologic storage sites (IEA Bioenergy 2023).

Using a proper functional unit and co-product management method are important LCA issues facing a BECCS technology that involves two products/services by definition: energy production and carbon sequestration. From a technology perspective, BECCS systems may operate across multiple geographic jurisdictions and generally entail several individual components in the supply chain. Robust LCAs benefit from detailed process descriptions and parameterization in all these stages. CO_2 transport and geologic CO_2 storage are also subject to specific measurement, reporting, and verification (MRV) challenges. This best practices document seeks to inform practitioners regarding the best LCA practices to avoid ambiguities and facilitate transparency in this domain.

3. General recommendations and unique issues for BiCRS LCA

As a framework, LCA can be deployed across the entire product development spectrum from concept through commercialization. The benefits to integrating LCA into the early stages of a technology include technology screening, early identification of potential hotspots, or burden shifting. Responding to such findings are much easier and more cost-effective at an early stage while the design, materials, and processes are still under development (Bergerson et al. 2020). While there is benefit in performing LCA earlier in the development cycle, it is also more challenging because it involves inherently more uncertainty across all phases of the assessment as it is an entirely prospective evaluation of potential impacts as opposed to a retrospective look at legacy impacts.

According to ISO 14040/14044 standards, an LCA encompasses four primary stages, as illustrated in Figure 2:

1. Goal and scope definition
2. Life cycle inventory analysis
3. Life cycle impact assessment
4. Interpretation

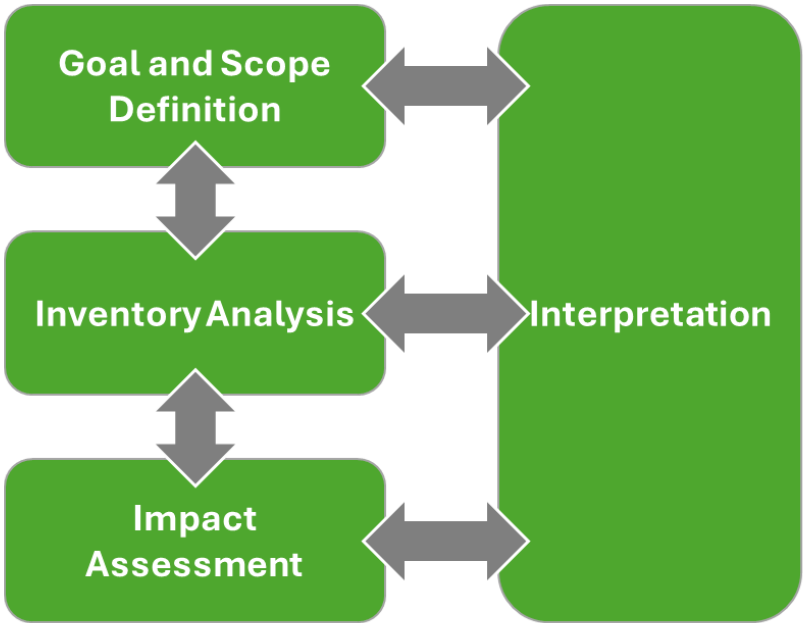


Figure 2. LCA Stages. Adapted from ISO 2006a.

Each life cycle stage is broken down into the key decisions that must be made in accordance with the ISO 14040/14044 framework. We discuss these key decision areas in subsections below. Each subsection is organized as follows:

- Brief background discussion of the key decisions that must be made within the life cycle stage.
- Relevance of those decisions to the application of LCA to BiCRS.
- Recommended best practices for those decisions.

Note: This document is not intended as a replacement for ISO 14040/14044, nor does it specifically address each of the items addressed in those standards. Rather, it should be viewed as a companion document when evaluating BiCRS.

3.1 Goal and scope definition:

A life cycle study starts with the goal definition by clearly defining the question(s) intended to be answered by the study. Life cycle assessment quantifies the environmental impacts of a product or service system on a relative basis with respect to its functional unit.

3.1.1 System boundary

Background

The system boundary for an LCA defines which system processes are included and excluded from the assessment. The choice of the system boundary is directly linked to the goal of the study. According to ISO 14040, processes can be excluded to the extent that they do not significantly change the outcome of the study. All exclusions should be documented and justified.

When evaluating a comparison of two LCA studies, consistency in boundaries is just as important as consistency in functional unit. While two studies with an equivalent function can be compared, if there are differences in the system boundaries, the result of the comparison will be misleading.

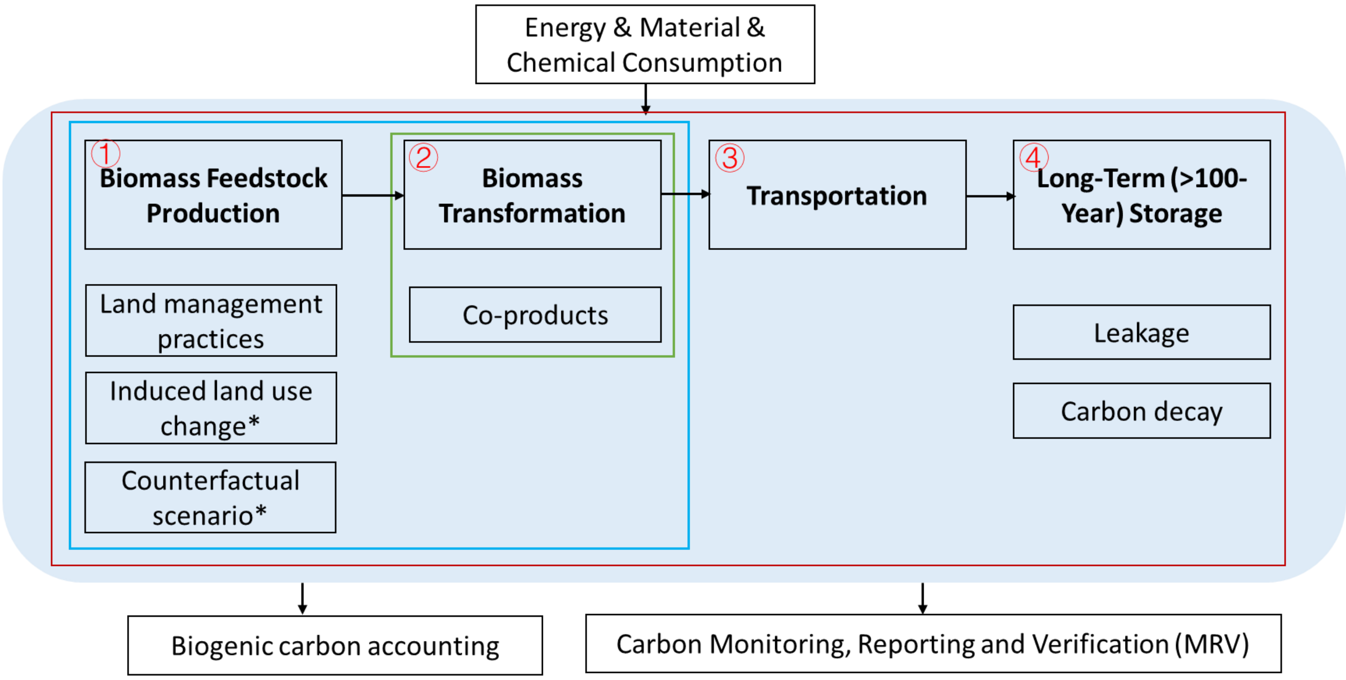
While boundaries for each system are often unique, a set of generic terms exists to refer to processes included or excluded:

- Cradle-to-grave: The most comprehensive set of boundaries, this term denotes all the activities associated with the production and/or sourcing of the biomass through carbon storage. Indirect emissions induced by mobilizing biomass feedstock for BiCRS (e.g., induced land use change) should also be accounted for in the cradle-to-grave analysis. See Figure 3 for a cradle-to-grave system boundary of a conceptual BiCRS technology. Note that biomass production may involve unique land management practices and may induce land use change. These direct and indirect effects associated with biomass production may have important GHG emission implications and need to be considered. In addition, certain types of biomass (e.g., residue biomass or organic waste resources) may undergo typical management practices when they are not sourced for a BiCRS technology. When such biomass sources are used in a BiCRS technology, the net GHG emissions or net carbon storage from regular management practices of such biomass present avoided net GHG emissions or foregone net carbon storage. These are commonly referred to as alternative fate or “counterfactual” impacts. They should be included in the LCA system boundary for dedicated BiCRS and BECCS technologies, with distinct and separate accounting for transparency.

While a cradle-to-grave assessment is always preferred, in some cases the end use and end-of-life for certain products and processes may be unknown or uncertain, so the appropriate unit processes corresponding to the boundaries should be included. Since the system boundary selected is linked to the goal of the study, BiCRS systems require a cradle-to-grave boundary to fully evaluate the stated function of biomass carbon removal. This boundary represents a complete accounting throughout the life cycle that is useful for markets and considerations in a policy context (e.g., evaluating different BiCRS approaches).

It is worth noting that special attention must be paid to the boundaries when comparing alternative BiCRS approaches for the same function. A truncated cradle-to-gate boundary may be used for consistent technology comparison with the same final disposition of biomass carbon (i.e., different BiCRS technologies). In application, the difference between these two boundaries in practice is the exclusion or the inclusion of the transportation and disposition of the biomass carbon for durable storage.

- Gate-to-gate: This boundary only encompasses the operations at the BiCRS facility. The technical and intermediate flows cross the boundary, but the resulting supply chain impacts associated with the upstream and downstream processes that create or transform those flows are not accounted for. Only emissions directly from the operations of the BiCRS facility are accounted for with this boundary.
- Cradle-to-gate: A modification of the gate-to-gate boundary, in which all processes upstream of the operations of the BiCRS facility are included back to the production and/or sourcing of the biomass. None of the downstream processes from the BiCRS facility are included.



**If applicable.*

Figure 3. System Boundaries, Life Cycle Stages, and Associated Unique Issues of A Conceptual BiCRS Technology. Cradle-To-Grave Is Signified by A Red Box, Encompassing Life Cycle Stages 1–4; Cradle-To-Gate Is Signified by A Blue Box, Encompassing Life Cycle Stages 1 and 2; and Gate-To-Gate Is Signified by A Green Box, Encompassing Life Cycle Stage 2.

Emissions associated with the consumption of process energy, materials, and chemicals or consumables across life cycle stages of a system boundary of choice should be accounted for. In addition, non-consumables (such as the manufacturing of capital equipment, infrastructure including but not limited to construction of storage site, well drilling and sealing, and other non-routine facility inputs not directly tied to normal operations) that generally occur prior to the operation of a BiCRS system and incur the emissions are often referred to as embodied emissions. Similar to the best practices on embodied emissions of non-consumables with regard to DACS (Cooney 2022), such emissions should also be included by amortizing the one-time or non-routine embodied emissions over the designed, cumulative storage capacity of CO_2 emissions/biomass carbon throughout the expected service life of the non-consumables. A complication for attribution of embodied emissions would be whether the storage infrastructure and other non-consumables can be reused or if it's single-use. Reuse of non-consumables could extend the storage capacity and possibly reduce the embodied emissions per tonne of stored carbon.

Best practices

- Evaluate BiCRS with a cradle-to-grave boundary to fully account for the function of the system.
- Depict the system boundary and encompassing processes graphically using a process flow diagram and justify any excluded unit operations.

- Accounting for indirect emissions such as induced land use change emissions, and distinct separate accounting for emissions implications from alternative fates, if applicable.
- Accounting for embodied emissions associated with non-consumables, considering storage capacity over the service life and likelihood of reusability.

3.1.2 Functional unit

Background

As noted in ISO 14044 (ISO 2006a, 2006b), "the scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied." The choice of the functional unit is linked directly to the goal and scope of the LCA. In the context of an LCA, the functional unit has multiple uses. First, it must clearly describe what the product or service does and the corresponding characteristics that define it. This allows the functional unit to serve as a consistent basis for comparison for multiple alternatives. Systems that do not yield the same function are unable to be compared unless the constituent systems are modified such that they provide a consistent function. Second, the functional unit services a practical role as the primary reference flow in the LCA model to which all inputs and outputs are quantitatively related and scaled. At early stages, multiple possible functions may evolve over the development and integration of a product or process into a larger system.

The functional unit and system boundary are also linked. The expansion (or contraction) of the boundary to include (exclude) additional elements of the life cycle directly affects the functional unit.

Relevance to BiCRS

The function for BiCRS is untraditional in the sense that it provides an environmental good—that is, the functional unit is in the same unit as one of the evaluated impact categories (i.e., climate change) and thus represents an iterative analytical requirement – i.e., the functional unit is a fixed amount based on the outcome of the LCIA for the climate change impact category. The overall goal of the LCA should also be considered when selecting a functional unit. Example functional units that could be (or have been) used to evaluate BiCRS systems include:

1. Per tonne of CO_2e of biomass carbon that is buried and stored for 100 years or longer.
2. Per tonne of biogenic CO_2 from biomass conversion that is captured and stored for 100 years or longer.
3. Per tonne of CO_2e of biomass carbon in biomass-derived solid or liquid products that is stored for 100 years or longer.

These functional units are similar in that only the biogenic carbon originating from biomass that is captured and stored is considered carbon removal. In addition, the timescale of durable carbon removal and storage is consistent, i.e., 100 years or longer. The main difference among these example functional units is the description of the form of the biomass carbon that may vary from gaseous CO_2, carbon in biomass-derived liquid products such as bio-oil, and carbon in biomass or biomass-derived solid products such as biochar, depending on the biomass conditioning and/or conversion strategies. Since these functional units are all based on the same amount of carbon from the biomass that ends up stored for the same timescale, they establish a consistent basis for comparison of a wide spectrum of BiCRS technologies.

To quantify the net CO_2e durably stored for at least 100 years for a BiCRS technology, both carbon uptake in biomass and GHG emissions that occur within the system boundary must be accounted for, see Section 3.1.4. For residual and waste feedstocks, the GHG emissions from alternative fates should also be considered, but accounted for separately as discussed later in this document.

When a gaseous CO_2 stream from a BiCRS facility is targeted for capture and storage, for the purposes of being able to compare with different CDR approaches, the basis for the analysis should be gaseous CO_2 pressurized to

2,200 psig and contain a minimum of 95% CO_2 by volume and not exceed any of the other established component limits established in the National Energy Technology Laboratory's CO_2 Impurity Design Parameters (IPCC, 2005; NETL, 2019).

It is worth noting that many BiCRS systems provide co-products or ecosystems services besides biomass carbon removal. These co-products, if applicable, must be handled appropriately according to a functional unit of choice. For example, a system expansion method is one of the co-product management methods that could be used to estimate the avoidance of emissions from producing conventional counterparts. In this method, the emissions avoidance is attributed to the net GHG emissions of biomass carbon removal that is addressed with a recommended functional unit listed here. Note that the value of the avoidance is subject to change over time as the product to be displaced may change, and the emissions associated with the displaced product may change. Section 3.4 has more detail on co-product management methods. It is recommended to differentiate between *removed* and *avoided emissions*, when the system expansion method is applied, which improves the clarity of the LCA co-product management methods and informs the efficacy of BiCRS technologies.

While the stored carbon may have broad dispositions, e.g., the captured CO_2 can be utilized for enhanced oil recovery (EOR) or transformed to another product via a conversion process, these use cases are beyond the system boundary of BiCRS. They require an extended system boundary and new functional units to represent the functions of the expanded system and the associated products or services, in addition to the carbon removal service of a BiCRS technology. The functional unit recommendation in this document directly addresses the goal and scope of an LCA of BiCRS, which primarily focuses on removal and storage of biomass carbon, with or without bioenergy production.

Best practices

- Analyze BiCRS using this functional unit: Mass of carbon from the biomass that ends up stored durably for at least 100 years, regardless of the forms of the stored carbon resulting from various biomass conditioning and/or conversion strategies.
- Report the net CO_2e removal per tonne of carbon from the biomass that is stored durably for at least 100 years.
- For CO_2 capture and storage at the downstream gate of a BECCS facility, the CO_2 should be compressed to 15.3 MPa (2,200 psig) and contain a minimum of 95% CO_2 by volume (IPCC 2005; NETL 2019).

3.1.3 Defining comparison systems

Background

One of the purposes for convening an LCA may be to compare potential alternatives. According to ISO 14044, a comparative assertion is an "environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function."

The decision to make a comparative assessment should be documented as part of the goal of the study. ISO stipulates that all the data quality requirements must be fully specified, documented, and addressed as part of the comparative LCA. Prior to interpreting the results, the equivalence of the systems under study must be evaluated according to the following elements:

- Functional unit.
- System performance.
- System boundary.
- Data quality (e.g., temporal, geographical, and technological representation [Edelen and Ingwersen 2016]).

- Impact assessment (see Section 3.3).
- Allocation procedures (see Section 3.4).

Relevance to BiCRS

As BiCRS technology continues to develop, it may be desirable to make comparisons for different pathways and vendors. Further, as the suite of potential CDR approaches emerges, comparisons likely will be made with BiCRS.

There are potential challenges when using LCA to compare emerging technologies at different stages of development. For early-stage technologies, the performance of the system will change as it moves closer to demonstration or commercialization (e.g., from increased process or material efficiency due to economies of scale). Temporal uncertainty also exists regarding when the emerging technology in question will deploy at scale and what the market and technology landscape will be at that future point.

Best practices

- Ensure functional equivalence between systems, including the management and provision of relevant alternative fates and co-products for all systems under evaluation.
- Document assumptions regarding the future landscape into which the BiCRS technology might be deployed at scale, including identifying technology improvement over time.
- Use consistent assumptions and data quality requirements for background data for all systems to ensure equivalent comparability.
- Represent the system boundaries for the different systems visually to communicate consistency when comparing two or more BiCRS or CDR systems.

3.1.4 GHG metric

To address the climate impacts of BiCRS, net CO_2e emissions, a metric centering on GHG accounting of a BiCRS technology is recommended.

The net CO_2e emissions are intended to calculate the net CO_2e emissions or removal for one tonne (or a similar unit) of biomass carbon removal and storage by a BiCRS technology. It is calculated using Equation (1):

$$NE = \frac{(-S+E_{P,F}+E_{p,bio_C}+Bio_{C_L})}{(Bio_{C_S}-Bio_{C_L})} \quad (1)$$

Where:

NE is the net CO_2e emissions of a BiCRS technology;

$-S$ is the carbon drawdown during biomass production;

E_{P,Bio_C} are biogenic CO_2 emissions from processes of the BiCRS technology;

$E_{P,F}$ are GHG emissions from processes of the BiCRS technology excluding E_{P,Bio_C};

Bio_C_S are the CO_2e of the biomass removal and storage for at least 100 years;

Bio_C_L are the physical leakage of biomass carbon after storage.

Note that the NE calculated with Equation (1) are simplified results that do not incorporate potential temporal carbon dynamics associated with the time lag between biogenic carbon uptake during biomass production and the biogenic carbon capture and storage brought about by a BiCRS technology. These results do not include any indirect emission effects such as induced land use change, which may be applicable. They also do not include any applicable GHG emission impacts stemming from alternative fates, which may be avoided emissions or foregone carbon sequestration. For the indirect and alternative fates-based emission impacts, which are considered consequential emissions collectively, it is recommended that they be estimated and reported separately, using Equations (2) and (3), and presented together with the NE results that are calculated using Equation (1).

$$E_{C,NCR} = \frac{-E_C}{(Bio_{C_S} - Bio_{C_L})} \quad (2)$$

$$E_{I,NCR} = \frac{E_I}{(Bio_{C_S} - Bio_{C_L})} \quad (3)$$

Where:

$E_{C,NCR}$ are the GHG emission impacts from alternative fates, whenever applicable, per tonne of biomass carbon removal and storage;

$E_{I,NCR}$ are the indirect GHG emission impacts, whenever applicable, per tonne of biomass carbon removal and storage;

E_C are the GHG emission impacts from alternative fates, whenever applicable;

E_I are the indirect emission effects including induced land use change, whenever applicable.

3.2 Life cycle inventory analysis

The Life Cycle Inventory (LCI) stage involves gathering all the key inputs and outputs associated with all unit processes within the established system boundary, including both technical and elementary flows. Unit processes represent the smallest portion of a system for data collection and relate inputs to outputs via an established relationship. Data collection for the LCI includes both the physical flows between processes (e.g., a process demands X kWh of electricity), but also the associated emissions in the value chain for that flow (e.g., Y kg CO_2e per kWh of electricity).

When collecting data for the purposes of an LCA, it is helpful to differentiate between the foreground and background of a system. The foreground represents the direct operations of the primary process or technology of interest and which the technology operator can directly influence, whereas the background includes all the supporting upstream and downstream processes (i.e., value chain) where the technology operator has limited impact. Thus, the representation of the foreground system should be detailed and complete enough to characterize the operational conditions and technology performance, such as biomass sourcing and handling, process energy and chemical requirement of BiCRS operations, construction and maintenance of the BiCRS facility, and throughput of carbon removal, whereas the background database should be transparent, up-to-date, and consistent for LCA of broad BiCRS technologies. The common theme across all the studies is the relationship between the amount and carbon intensity of the energy that is used to run the process, such as electricity and heat, and the net storage of carbon from the biomass that the facility achieves. For completeness, all energy and material inputs should be included. The LCI data should be periodically reevaluated and updated as a BICRS technology matures and is deployed at scale.

This section separates data collection into two groups: consumables during facility operation (those that occur routinely) and non-consumables (those occur on a one-time basis).

3.2.1 Data collection: consumables during facility operation

Background

The plant operation includes the activities and processes that would be included in a gate-to-gate system boundary. It is also generally referred to as the foreground system. Depending on the study, the representation of plant operations can range from a black box depiction to a detailed dynamic process model that is linked to the LCA. During this data collection activity, it is important to gather all information about the physical flows of inputs and outputs from this boundary, inclusive of raw materials, energy, emissions, products, and wastes. This information will then link to the modeling of background system impacts associated with the consumables required by the facility.

For mature systems, the facility of interest is usually operational, meaning that the required information is readily accessible. With earlier stage technologies, the information that is used to represent the system comes from process engineering models that use fundamental engineering relationships to characterize the system.

Relevance to BiCRS

Engineering simulations are used to characterize energy and material balance of facility operations for early-stage BiCRS technologies. It should be noted that the scope of these models is variable and additional estimates or data sources may be required to fully characterize the facility operations (e.g., emissions species not tracked by the engineering model). As technologies materialize and are introduced to the market for potential future regulatory compliance and policy incentive, MRV (measurement, reporting, and verification) of foreground data will become increasing important and necessary.

For BiCRS, in addition to the biomass feedstock, the following process consumables at the facility should also be included in the LCI:

- Energy:
  - Imported heat, reported in lower heating value (e.g., embodied in steam), and associated technology mix (e.g., steam sourced from Natural gas).
  - Imported grid electricity and associated grid mix (e.g., % Coal, Natural Gas, Nuclear, Solar, Wind, etc.).
- Process chemicals/materials:
  - Acids/base for pretreatment.
  - Catalysts.
- Water
  - Make-up water.

Best practices

- Report physical quantities for inputs and outputs (including both carbon removal and bioenergy production, if applicable) in addition to the associated inventory of emissions.
- Separately report and account for any captured fossil or other non-biomass-derived CO_2 (e.g., from on-site fossil fuel combustion) from the biomass carbon that is captured and stored for consistency with the functional unit.
- Coordinate with the process engineering modeling team and/or facility operators to compile operational energy and material balance data necessary for LCA, including physical quantities for process inputs and outputs (e.g., MJ energy, kg materials) in addition to the associated inventory of non-combustion emissions (e.g., kg non-combustion emissions).

- When multiple potential sources/types are being evaluated as part of the design, develop separate LCA scenarios for each.
- Clearly identify degrees of uncertainty and variability, particularly for modeled rather than measured inputs.
- Consider changes in facility-level consumables over time.

3.2.2 Data collection: non-consumables

The processes included in this category generally occur prior to operation, and the corresponding emissions are often approximated as one-time impacts. These include a combination of non-routine plant inputs as well as manufacturing of capital equipment and site construction. The amounts of these materials do not change as a function of variability in the production of a facility (e.g., a facility that operates full-time versus part-time). Since these emissions associated with these activities are not directly tied to ongoing operations, they are amortized over the expected life of the operation so that they can be normalized to the functional unit. See Equation (4):

$$\frac{mass\ of\ emissions}{functional\ unit} = \frac{Total\ emissions\ associated\ with\ non{-}consumables + Replacement\ Emissions}{Facility\ design\ capacity \times Capacity\ factor\ \times Operational\ lifetime} \tag{4}$$

Where:

- $Total\ emissions\ associated\ with\ non - consumables$ are upfront mass of emissions;
- $Replacement\ Emissions$ are additional emissions from replacement of non-consumables throughout the operational lifetime;
- $Facility\ design\ capacity$ is the facility-level mass CO_2 removed per year;
- $Capacity\ factor$ is the percentage time facility is operational on capacity over the course of one year;
- $Operational\ lifetime$ is the lifetime of the facility, in years, while operational.

Several different approaches can be used for developing inventory data to represent these activities:

- Material/equipment list from a TEA and translation to the base material inventories developed by process LCA methods (e.g., structural steel, concrete, etc.).
- Emission profiles from manufacturer Environmental Product Declarations (EPDs) and publicly available LCA database such as openLCA.
- Economic input-output (IO) modeling is an approach that maps expenditures to different economic sectors, which are then tied to emissions associated with those sectors (Chen et al. 2018; Weber et al. 2009; US EPA 2023).

It should be noted that there may often be uncertainty in these processes, especially for emerging technologies. The effect of this uncertainty on the overall results should be explored by using reasonable proxies and ranges for the process in question. Also, multiple approaches can be used as necessary to best provide a complete representation of these materials. Depending on the stage in development, some approaches may be more reasonable than others (e.g., use of IO methods at low TRL prior to the completion of a comprehensive TEA).

Relevance to BiCRS

Like other industrial processes, the relevant processes for BiCRS likely include the following:

- Manufacturing capital equipment.
- Site construction and maintenance.

Best practices

- Compile a bill of material/equipment data for the actual facility construction, when available.
- Use a modeling approach that provides the best data available to represent these activities corresponding to the stage of development.
- Update representation of design and underlying LCI data as technology matures and nears deployment.
- Test sensitivity of the assumed facility lifetime and any non-consumables that require replacement during the facility operating life.

3.2.3 Data collection: key processes and potential data sources

A variety of LCI data sources exist, both public and commercial (e.g., ecoinvent, GaBi, etc.). Public data sources from the DOE and federal government are provided below:

- National Energy Technology Laboratory (NETL)
  - Natural gas model
  - Gate-to-gate saline aquifer storage model
  - U.S. Electricity Baseline
    - Grid Mix Explorer Excel tool
    - openLCA Unit Processes
  - Unit Process Library
- Argonne National Laboratory (ANL) The Research and Development Greenhouse gases, Regulated Emissions and Energy use in Technologies (R&D GREET) model (Argonne National Laboratory, 2023)
  - LCI of energy inputs
  - LCI of materials inputs
- U.S. Federal LCA Commons (Federal LCA Commons, 2024)
  - NREL U.S. Life Cycle Inventory (USLCI) database
- U.S. EPA Environmentally-Extended Input-Output (USEEIO) Models (EPA, 2023)

Table 1 provides an overview of the key process inputs that may need to be gathered as part of the LCI. U.S. DOE and other federal resources are provided for each.

Table 1. Key Process Inputs for LCI Data Development

LCI Data Category	Parameters	DOE and Other Federal Resources
BiCRS operation	Inputs and outputs associated with the facility operations, including the biomass feedstock and any on-site emissions	Unique to each project – user input based on engineering model or actual operational data
Consumables – Electricity	• Consumption mix technology contributions by generation type • Inclusive not only of generation facility emissions, but also fuel and material supply chains, where applicable • Future grid mixes based on proposed year of deployment using data provided in EIA's Annual Energy Outlook "Reference Case"	• U.S. Electricity Baseline (NETL) – regionalized consumption mixes with options to customize technological representation • Regionalized electricity generation mixes with projections in ANL R&D GREET

LCI Data Category	Parameters	DOE and Other Federal Resources
Consumables – Heat	• For on-site combustion: direct emissions should be included in DAC operation, but fuel supply chain (e.g., natural gas) accounted for separately • For offsite combustion: both fuel combustion and fuel supply chain should be accounted for	• NETL • ANL R&D GREET • Federal LCA Commons
Non Consumables – Construction/Capital Investment	Amounts (mass) of key materials (e.g., steel, concrete, aluminum, copper, glass) for process equipment and site infrastructure	• Process-based LCA could be conducted using material LCI data from NETL, R&DGREET, Federal LCA Commons • Alternatively, to estimate data based on purchasing, could leverage U.S. EEIO approach
Consumables – Process Chemicals and Water	Inclusive of initial system charges as well as any required routine makeup over the life of the facility (catalysts, etc.)	• Highly dependent on the chemical – some data are available from NETL, R&D GREET, and U.S. LCI • Alternatively, to estimate data based on purchasing, could leverage U.S. EEIO approach
CO_2 compression, transport, injection, MRV	Initial on-site compression of the captured CO_2 should include the BiCRS site electricity consumption, as well as required boost compression and transport. Storage site activities include site prep, well construction, injection, brine management – these are all variable by site and could be parameterized if desired to evaluate geographic/geologic variability MRV includes activities to ensure robust storage and reporting of any leakage that occurs.	NETL gate-to-grave assessment of saline aquifer storage of CO_2
Waste management	Handling, transport, and management of any process wastes from BiCRS operations	U.S. LCI for landfilling or incineration; R&D GREET or NETL for transport
Land use change	Site disturbance/clearing to facilitate BiCRS operations and infrastructure	R&D GREET and NETL have land use change/conversion factors
Decommissioning	Deconstruction, waste disposal, material recycling	Proxy industrial facility for these impacts (e.g., power plant decommissioning is included in some of the NETL LCAs)

3.3 Life cycle impact assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) Phase pertains to the translation of LCI emissions into potential environmental impacts based on the selection of a particular set of categories and characterization factors. According to ISO 14044, "The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration."

The results of the LCIA stage depend heavily upon the decisions and data collection in the earlier stages of the LCA. The choice of system boundary and functional unit, availability, and representativeness of the LCI data, and the characterization methods used all affect how meaningful and comparable a set of LCIA results are. Significant geospatial and temporal variability also may not be accounted for in the impact assessment methods.

Relevance to BiCRS

While the primary focus in evaluating BiCRS and other CDR systems in an LCA context is the quantification of the net carbon dioxide (equivalents) removed in the form of biomass or biomass-derived carbon carriers, LCA provides a basis for evaluating other potential environmental impacts allowing for an assessment of the potential tradeoffs between them. This more holistic view is how LCA differs from carbon footprinting. BiCRS LCA should consider broad environmental impacts besides the net carbon removal.

Best practices

- Several methods exist to assess broad environmental impacts, such as AWARE, CML-1A, Recipe 2016 (endpoint/midpoint impacts), IPCC 2021, and IMPACT 2002+, among others (openLCA 2024). It is recommended to use the EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 method for LCIA (US EPA 2021) to characterize the following impact categories (additional impact methods and impact categories may also be reported): ozone depletion, acidification, eutrophication, smog formation, human health particulate, human health cancer, human health noncancer, ecotoxicity.

TRACI 2.1 was last updated in 2012 and thus does not reflect the latest global warming potential characterization factors from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (see Table 3). It is recommended to use the IPCC AR6 GWP characterization factors for translation of GHG emissions to Global Warming Potential impacts as a replacement for the factors in TRACI (IPCC 2021), and adopt future IPCC GWP characterization factors as they are released. Note, depending on the use case for the LCA, other vintages of the IPCC GWP factors may be required. For example, the international GHG reporting standards under the United Nations Framework Convention on Climate Change (UNFCCC) require the use of the GWP values from the IPCC's Fifth Assessment Report (AR5), published in 2013. The LCA should be clear about what factors were used for the calculation of the GWP. It is recommended that the inventory of individual GHG emissions be included so that conversions to other vintages can be made as needed for comparison purposes.

Table 2. Twenty-Year and 100-Year GWP Values of Fossil CH_4, Biogenic CH_4, and N_2O, Relative to That of CO_2. Source: Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change.

GHG	20-Year	100-Year
CO_2	1	1
Fossil CH_4	82.5	29.8
Biogenic CH_4	79.8	27.1
N_2O	273	273

3.4 Co-product management

Background

Co-product management refers to a set of approaches to handling BiCRS systems with multiple products leaving the system boundary. In these systems, it is often desirable to produce results on the basis of a single product. ISO 14044 prescribes the following hierarchical approach for managing co-products:

1. Avoid allocation by
   a. Subdividing the system into sub-processes with individual products and model those sub-process inputs and outputs accordingly.
   b. Expansion of the system to include the functions of all products leaving the system boundary.
2. Partition (allocate) the inputs and outputs of the system "in a way that reflects the underlying physical relationships between them." Typical bases for the physical relationship include mass and energy value.

3. Use an alternative allocation basis when a physical relationship cannot be established—e.g., economic value.

While subdivision is the preferred approach in ISO 14044, for complex and heavily integrated systems it is often infeasible due to data limitations. The next preferred approach, system expansion, essentially solves the issues of co-products by including them in the functional unit. This approach removes any of the potential subjectivity introduced in the subsequent approaches, but with the drawback that it renders comparison with other systems more difficult because the system in question no longer produces a single product, but multiple products. Any comparison in LCA must be based in principle on equivalence in function. For this reason, some practitioners have added a subsequent step to the system expansion process and take credit for the avoided production via conventional means of the system's co-products. This approach is often referred to as system expansion with displacement. It is also referred to as "substitution" or "avoided burden." An alternative approach when using system expansion is to modify the comparison system to include the additional processes necessary to ensure equivalent function with the system under study.

It should be noted that the use of system expansion with displacement can result in net negative flows of emissions in the life cycle inventory. These negative values do not imply uptake of emissions (e.g., carbon dioxide) from the environment, but rather that evaluated system for producing the primary output is environmentally preferred to the comparison approach for the impacts evaluated, especially when the co-product(s) represent a large share of the total product slate. Baselines should be clearly identified, and displacive impacts should be identified as such. When an allocation method is applied, the choice of the allocation basis, e.g., mass or energy or market value of the main product and co-product(s), may consider the potential inequivalence among the products on a given basis (e.g., the mass of CO_2 removal vs the mass of bioenergy produced). In such cases, weighting factors may be considered to correct the inequivalence. Alternatively, a different allocation basis with a less degree of inequivalence among the products may be preferred.

Relevance to BiCRS

For BECCS, both energy products and carbon removal service are provided and must be addressed in the context of a multifunctional system. Even for dedicated BiCRS technologies focusing on below-ground storage of biomass-derived products, co-products besides carbon removal might present.

By necessity, co-products are managed throughout LCI databases to provide LCI data on the basis of a single product that may be used as an input to another process. Where different options exist, a consistent approach should be considered for both the foreground and background data to the maximum extent feasible.

Best practices

- Follow the established co-product management hierarchy in ISO 14044 Section 4.3.4.
- If subdivision is not possible, use system expansion with a multiproduct functional unit.
- Negative emissions associated with displacement of co-products should always be accounted for separately and transparently.
- Maintain a record of the physical system depicting the impacts with and without management of co-products.
- Test multiple co-product management approaches, including allocation. This can help determine how robust conclusions are across multiple approaches.

3.5 Unique issues for BiCRS LCA

The following section outlines a range of issues related to BiCRS that are unique compared to LCA of biofuel production using agricultural feedstocks *without* carbon capture systems (e.g., corn ethanol), fossil-based energy production systems with carbon capture (e.g., NGCC with CCS). Unique LCA treatments are required for BiCRS because of both the nature of the biomass-based feedstocks that may be used, in particular for dedicated BiCRS systems (unique versus first generation biofuels) and the storage component of BiCRS (unique versus bioenergy without CCS, and NGCC). The fact that woody biomass feedstocks are likely the most prevalent feedstock for dedicated BiCRS system requires intentional and *explicit accounting of biogenic carbon* associated with the production, collection, and use of that feedstock from the landscape along with the CO_2 sequestered to ensure that quantifications of net removals are technically sound and robust. An alternative to explicit accounting of biogenic carbon is an assumption that the biogenic carbon emissions involved with a bioenergy system are net neutral. That is, the CO_2 emitted from the combustion, gasification, or processing of the biomass into the energy product(s) is equal to – or offset by – the CO_2 sequestered from the growth of the biomass. The following sections outline why that simplified assumption is not appropriate for BiCRS LCA, and Appendix A2 provides additional details on different biogenic carbon accounting approaches.

Different types of biomass feedstocks warrant different types of considerations based on their species, the type of landscape and production system they come from, and assessments of their alternative fates. For example, while chipped pine that was collected from downed-dead slash and chipped pine from pulp logs coming from a harvest may be indistinguishable, and have the same material characteristics, there are very different implications to the use of these two sources of chipped pine for an LCA including the need for evaluating different temporal and spatial scales for the biomass, different carbon implications of alternative fates (i.e., if not used for BiCRS), and potential market-mediated *leakage* or “indirect” effects (e.g., land use change emissions) from their use for BiCRS.

In general, the use of residual waste biomass that otherwise would not have any economic value would mean that feedstock could be collected and utilized for BiCRS without having leakage emissions effects. However, it should *not* be assumed by default that a given biomass material such as a forest residues are waste biomass. If a BiCRS project claims that their feedstock is waste biomass and does not have alternative value or use the onus should be on that project to substantiate this claim, and there should be. The fact that a feedstock may be a byproduct of a larger production process (e.g., mill residues) does not mean that feedstock is necessarily waste biomass. Byproducts could still have value and alternative uses which means that their use for BiCRS could lead to leakage effects. Further, the assignment of a feedstock as waste biomass should not necessarily be a permanent treatment. Evolving dynamics on the landscape, the rise of new markets, or the scale of collection and utilization efforts could change the characteristics of a feedstock. Additionally, an assessment that a feedstock may be appropriately deemed waste biomass in one location does not mean it necessarily is universally (e.g., forest residues may not have economic value and market uses in region X, but it may in region Y). Feedstocks - and the potential leakage impacts from there use – should be evaluated on an individual project basis.

3.5.1 Baselines

Background

Baselines are assessments of what has happened or estimates of what will happen absent an intervention. They are required for LCAs involving consequential assessments to estimate emissions *changes* from a policy change or technology development, often referred to as *indirect emissions* in instances where there may be leakage effects. Baselines can either be static - comparing indicators at a current or historical point in time, or forward looking – consider the dynamics of physical and economic systems over time. Attributional LCA’s, or the attributional portions of LCAs, do not always require baselines. Attributional LCAs, which estimate *direct emissions*, identify and quantify emissions activities and flows in a system, and assigns or allocates emissions across different products. Attributional LCA’s are valuable for evaluating changing performance for a given technology over time or under different conditions and comparing the environmental performance of different technologies agnostic of most baseline conditions or changes over time. Consequential LCAs are useful, and necessary, for evaluating overall emissions changes associated with a policy or project in specific circumstances, and can be either static (i.e., looking at a “snap shot” of impacts) or dynamic (i.e., looking at the sum of changes over time), and inherently require baselines.

Relevance to BiCRS

Baselines help an LCA practitioner evaluate what would happen absent BiCRS deployment as a way of assessing the net emissions footprint of new technology deployment. Establishing reliable baselines is crucial for BiCRS LCA, enabling consistent accounting of net CO2 removal and ensuring the complete assessment of BiCRS technology impacts when considering policy or carbon market applications. The ability to evaluate and estimate the consequential impacts is important for evaluating the overall efficacy of individual BiCRS projects and collective deployment of BiCRS as a CDR strategy.

Best practices

- A baseline should be developed for purposes of estimating leakage impacts
- The selection of a baseline and assumptions being made about baseline conditions should be clearly documented
- A baseline should always be used when evaluating the LCA of an actual project with potential leakage effects, while an LCA for R&D or comparative purposes can be made without the explicit choice of a baseline.
- A static baseline may be used for instances in which either there aren’t temporal dynamics associated with the biomass, or those dynamics are narrow and certain (in which case applying exogenous factors may be appropriate)

A dynamic baseline should be used for instances in which there are temporal carbon dynamics associated with the feedstock (e.g., dedicated forestry biomass).

3.5.2 Alternative fates

Background

Evaluating alternative fates and their emissions implications involves comparing the use of woody biomass, agricultural residues, or organic waste streams against scenarios where such carbon resources are not used in the way being considered (e.g., for BiCRS). This comparison helps assess the relative environmental benefits or drawbacks of technologies using such carbon resources by evaluating how they perform in contrast to other management strategies of the resources.

Relevance to BiCRS

Alternative fates related to woody biomass, agricultural and/or forest residues, and waste biomass may present opportunities to avoid the emission implications associated with the business-as-usual (BAU) management practices when such biomass is diverted to a BiCRS technology, or could result in additive emissions. Alternative fates may vary widely and will be case-by-case for specific BiCRS projects. For example, for woody biomass that may not be sustainably managed to maintain a constant biomass stock in the forest stand, the impacts of leaving the forest unharvested need to be assessed. This includes but is not limited to evaluating the natural carbon sequestration potential of standing forests, degradation of standing trees over time, and potential risks and consequences of losing carbon in the event of wildfires, especially in some western regions of the United States. For sustainably produced and managed biomass resources, the alternative fate may be continued management practices necessary to sustain the carbon stock in the biomass production system, e.g., thinning a managed forest stand. For residue biomass such as forest residues or crop residues, the baseline should reflect the BAU residue management practices, such as leaving the residues in the forests/crop fields for natural decay, prescribed burning, and accelerating or delaying harvests, as well as potential competing beneficial uses of the residues, such as making pellets. For organic waste such as biogenic solid waste or animal manure, the baseline should consider the BAU waste management practices, such as landfilling, storage in anaerobic lagoons, etc.

Alternative fates are not static; rather, they can change with evolving market conditions including the scale-up of the use of feedstock in a given region. For example, for the first BiCRS facility established in a region seeking to use downed forest residues that otherwise would be left on the forest floor to decay, considering this decay and associated emissions may be appropriate ("avoided emissions"). However, for the n^{th} BiCRS facility in the same region, the availability of such feedstock may be limited and may reach a point seeking to use downed forest residues, requiring the sourcing of different or additional sources of feedstock, for which a different alternative fate may apply.

Best practices

- It is important to discuss specific alternative fates that may be avoided solely due to diversion of the biomass to the development and deployment of the BiCRS technology. If multiple alternative fate may be expected, discuss the likelihood of each and conduct scenario analysis for each.
- Ensure that the alternative fate is realistic and relevant to the context of the biomass production or sourcing of waste/residue carbon resources by evaluating historical trends, business-as-usual biomass production/management plans, and market conditions for the specific source of biomass.
- Seek stakeholder input: Involve stakeholders in the appropriateness of alternative fates to ensure that they are relevant and reflect the perspectives of those affected by biomass production. Stakeholders may include local communities, policymakers, industry representatives, and environmental groups.
- Define an appropriate time scale for the alternative fate(s), considering both short-term and long-term impacts. The effects of biomass production/management may vary significantly over time.
- Consider the spatial scale of the assessment. Alternative fates may need to be evaluated at local, regional, or global scales, depending on the scope of the biomass production/management that are influenced.
- Consider the effects of different levels of additional demand for BiCRS on the availability of feedstock and potential impacts on alternative fates.
- Conduct sensitivity analysis to evaluate the geographic location and local environmental conditions that may affect emissions, carbon sequestration, and other ecosystem impacts in alternative fates.
- Emission implications of alternative fates should be quantified with the best available measurement, empirical, or modeling data.
- Assess broad ecosystem impacts that may be relevant. For example, assess how the use of forest biomass affects forest ecosystems, including biodiversity, soil health, and water cycles.
- Clearly document the data sources, assumptions, and methods used in the analysis of specific alternative fates to ensure transparency and reproducibility.
- Avoided emissions/foregone carbon sequestration based on alternative fates should be reported separately from carbon removals, following the best practices provided in Section 3.1.4.

3.5.3 Leakage

Leakage refers to emissions resulting from changes in the production or use of biomass feedstocks for BiCRS, and are typically driven by changing market conditions (e.g., changes in prices), relative to baseline conditions. A common form of leakage is emissions resulting from induced land use change (ILUC). Leakage can be emissions from the landscape (e.g., methane from rice paddy fields), or activity activity-based (e.g., emissions from additional diesel use in tractors). Additionally, changes in terrestrial carbon stocks are a form of leakage associated with changes in the production or use of biomass feedstocks for BiCRS that can occur as a one-time perturbation or series of changes and can have carbon implications that persist over time.

Emissions effects from leakage can be either positive or negative. That is, there can be either net contributions to the emissions associated with BiCRS, or net emissions savings that mitigate the emissions associated with BiCRS.

For example, additional demand for woody biomass for BiCRS could result in investment by forest managers that lead to *additional* carbon in the landscape relative to a baseline.

3.5.3.1 Induced Land Use Change

Background

Induced land use change (ILUC) is a form of leakage referring to changes in land use and land cover that occur when an increased demand for biomass feedstock for a BiCRS technology is being met via market signals. For example, increased demand for woody biomass can lead to the establishment of new plantations or the expansion of existing forests for biomass harvesting. This can involve converting other types of land to forests to meet biomass production needs, or it could lead to one-time forest clearing episodes in order for a landowner to capture higher prices to meet demands, without subsequent regenerative forestry. In addition, as land is repurposed for biomass production, other areas might be used differently. For example, agricultural land might be redirected to food production if biomass plantations are established on previously cultivated lands. Higher demand for woody biomass can increase the value of forest and agricultural lands, leading to further land conversion or changes in land use patterns driven by market forces.

Relevance to BiCRS

Production and mobilization of biomass feedstock for BiCRS such as purposely-grown herbaceous biomass, woody biomass, and oilseed crops may require additional land to grow such biomass and thus may induce land use change, such as conversion of non-biomass land, e.g., grassland, to new biomass land. The induced land use change may have GHG emission implications due to losses or enhancement of soil organic carbon (SOC) from one land use to the another. In addition, use of the land for growing new biomass may require new land management practices tailored to producing the biomass, potentially causing direct and indirect emissions associated with silvicultural or agronomic practices, which may result in changes in SOC and GHG emissions especially nitrous oxide (N_2O) emissions. Such indirect emission effects have been considered for such biofuels as corn ethanol, soybean biodiesel, sustainable aviation fuels produced from corn ethanol, and soybean biodiesel, among others. These indirect emissions need to be addressed for a BiCRS technology that uses a biomass feedstock at scale. To do so, economic models are needed to estimate possible land use changes in response to an increase in demand for the BiCRS biomass feedstock. In addition, soil process models such as CENTURY (Kwon et al. 2010) and DayCent (Del Grosso et al. 2001) may be needed to simulate potential changes in SOC and N_2O emissions that are associated with induced land use changes.

Best practices

- Clearly define the boundaries of ILUC modeling, including geographic scope, time horizon, and the types of biomass being evaluated (e.g., energy crops and woody biomass).
    - Modeling should have a geographic scope sufficient to encompass all relevant markets that may be directly (divert feedstock diversion) or indirectly (substitution of feedstocks) effected by BiCRS feedstocks.
- Employ economic and land use models that can capture the dynamics of global agricultural markets, land availability, and crop productivity. Models like Global Trade Analysis Project (GTAP) (Purdue University 2024) or Global Biosphere Management Model (GLOBIOM) are commonly used (IISA 2024), while models like A Land Use and Resource Allocation Modeling System (LURA), the Forest and Agricultural Sector Optimization Model (FASOM), and the Global Timber Model (GTM) can estimate dynamics of forest product markets, forestry land use (change), and associated carbon fluxes.
- Validate models with historical data and compare them with other models to ensure robustness and reliability in predicting ILUC.

- Develop multiple scenarios to capture the range of possible outcomes. Scenarios might include different assumptions about biomass demand, agricultural productivity, policy interventions, and technological developments.
- Consider how existing and proposed policies and carbon pricing influence land use decisions and the extent of land conversion.
- Assess how market dynamics, such as global commodity prices, influence the economics of land use change. The profitability of biomass production relative to other land uses is a key driver of ILUC.
- Perform sensitivity analysis to understand how changes in key parameters (e.g., biomass yield, demand for biomass) affect the results, highlighting which factors have the most significant influence on ILUC.
- Evaluate how ILUC affects carbon stocks, both above ground (forests, grasslands) and below ground (soil carbon). Include direct emissions from land conversion and indirect effects such as changes in agricultural practices and livestock production.
- Be transparent about the assumptions and limitations of the models and data used. This transparency helps stakeholders understand the uncertainty and variability in the results.
- Claims that there are not ILUC effects associated with the BiCRS feedstock should be thoroughly demonstrated (e.g., historical records that feedstocks have not had alternative uses, evidence of absence of suitable alternative uses).

3.5.3.2 Terrestrial Carbon Impacts

Background

There can be significant leakage impacts on terrestrial carbon stocks from changing production or use of biomass feedstocks, especially for woody biomass. Carbon in trees is a semi-durable form of carbon (in contrast to annual agricultural feedstocks). Left unperturbed, after a year a corn crop would die and decompose releasing the carbon stored in the biomass of the crop.[1] In contrast, left unperturbed and absent an environmental disruption such as insect infestation or wildfire, a tree would continue to grow and accumulate carbon. Further forest managers can make decisions to intensify or expand production which could lead to additional carbon on a landscape. Terrestrial carbon impacts can occur for above and below-ground biomass, and carbon in soils. For residues and downed-dead wood, there may also be terrestrial carbon impacts from the collection of these materials in the prevention of partial reabsorption of carbon in soils through the biomass decay process.

Relevance

Like any product grown on or produced from the landscape, a potential new source of demand, such as for BiCRS system, may impact the supply of that, and other products. Considering potential additional valorization of woody biomass through demand for BiCRS, price signals could generate supply responses that have carbon implications. For woody products, this effect can be considered in two broad forms. One, the effects on carbon stocks within a landscape such as a forest stand. In a forestry system, a forest manager can decide not to harvest at all in a year they'd originally intended to in response to market signals (i.e., delayed harvest), or alternatively they could accelerate harvests which would result in "foregone sequestration". In contrast to an acre of corn, which if unharvested would die and decay, a forest stand would continue to grow and accumulate carbon. Understanding if and how terrestrial carbon stocks and fluxes are affected by direct land use change as well as forest management changes is an important component of BiCRS LCA.

The second terrestrial carbon effect relates to market-mediated land use change and subsequent changes in carbon associated elsewhere. For example, if forest residues are diverted used for use for BiCRS, and they otherwise

[1] Not 100% of the carbon in the biomass would be emitted immediately; depending on the biomass type, climate, and landscape conditions biomass would decompose at different rates.

would have gone to other end uses, there may be a need for that supply to be backfilled, by increased production or diversion of residues elsewhere which may have terrestrial carbon implications that could mitigate the additionality of carbon storage from the BiCRS technology.

Results from these assessments will be subject to choices of the temporal scales to evaluate changes over, and spatial scales to evaluate changes across. There is no one correct *spatial scale* and *temporal scale* that should be applied universally. Decisions about the appropriate spatial scale should take into account several factors. One, the potential geographic breadth of leakage effects that may stem from the use of the biomass for BiCRS, i.e., if the feedstock was previously – or is a substitute to – a good that is internationally traded, the LCA should *encompass* impacts from the potential diversion of the material to those markets (e.g., biomass from the U.S. Southeast used to make pellets which are exported to the EU). Two, and related, for forestry biomass from managed systems the fuel shed from which biomass is sourced. Assumptions of temporal scales over which carbon fluxes are evaluated should take into account the historical, current, and future potential lifecycles of the feedstock. For example, a dedicated short-rotation hybrid poplar system which is harvested every 3-5 years, will warrant a shorter time scale than a U.S. Southeast pine forest system, which will warrant a shorter time scale than biomass from forest stands in the U.S. Northwest (potentially 100 plus years).

Over a long enough temporal scale, and in a continuously managed forest plantation system with a regular set of markets, these potential leakage effects may be limited or zero as forest managers engage in a carbon-stable planting, thinning, and harvesting schedule. But the introduction of a new potential source of demand for woody feedstock for BiCRS operation could perturbe forestry systems and result in leakage.

Best Practices

- For primary forestry feedstock for BiCRS (e.g., pulpwood), forest residues with alternative uses or value, or mill residues, modeling should be performed using one or models that can simulate interactions between forest product markets, and can directly estimate or feed into estimates of forest carbon stock changes. A Land Use and Resource Allocation Modeling System (LURA), the Forest and Agricultural Sector Optimization Model (FASOM), and the Global Timber Model (GTM) are examples of frameworks that can simulate these effects.
- Terrestrial carbon impacts should be considered over a *temporal scale* that capture the full lifecycle of feedstocks being affected. This will be shorter for shorter-rotation feedstocks, and longer for feedstocks with longer lifecycles.
- Terrestrial carbon impacts should be considered over a *spatial scale* that spans the potential direct impacts (e.g., BiCRS feedstock fuelshed) as well as indirect effects. Considered indirect effects should include effects on both the fuelsheds of any feedstock substitutes for regional energy or forest product end uses, as well as those involved in the trade of these feedstocks and products, and their associated fuelsheds.
- Sensitivity analysis should be performed to examine the impacts of results against different assumed spatial and temporal scales to understand the range of outcomes depending on the assumption, and the robustness of the overall BiCRS LCA results.

3.5.4 Co-products and co-benefits

Background

A co-product is a valuable material produced along with the primary product, which offers additional utilities when valorized. On the other hand, other types of outputs are considered waste, residues, and by-products. These are not intended for use and are often disposed of with little to zero economic values. Because waste, residues, and by-products are not considered as the primary goal of the process, emission burdens are not allocated to these streams. ISO 14040/14044 (ISO 2006a, 2006b) recommends allocation by subdividing the system into sub-processes or expanding the system boundaries. When these approaches are difficult to apply, allocation methods based on physical relationships could be used (e.g., energy allocation or mass allocation) to proportionally share the environmental impacts among the products. Finally, economic value-based allocation could be applied when other preferred methods are difficult to apply.

Co-benefits are positive impacts or advantages that arise from BiCRS systems beyond the primary goal of biogenic CO_2 removal. These benefits often contribute to sustainability and can make BiCRS projects more attractive. Examples include:

- Soil and water conservation: Some biomass feedstocks such as perennial grasses can help prevent soil erosion, improve soil structure, and reduce nutrient runoff, benefiting overall soil and water conservation efforts.
- Waste management: Using biomass residues or waste products (e.g., agricultural residues, forestry by-products, organic municipal waste) for BiCRS could help manage waste and reduce emissions associated with waste management.

Relevance to BiCRS

In BECCS, various processes may convert biomass into valuable products while process CO_2 emissions are captured and sequestered (Figure 4). For example, a fermentation process converts corn or other biomass into ethanol; meanwhile, high-purity CO_2 from the fermentation process is captured and sequestered underground. Or, electricity is generated from biomass combustion, and combustion emissions can be captured and sequestered.

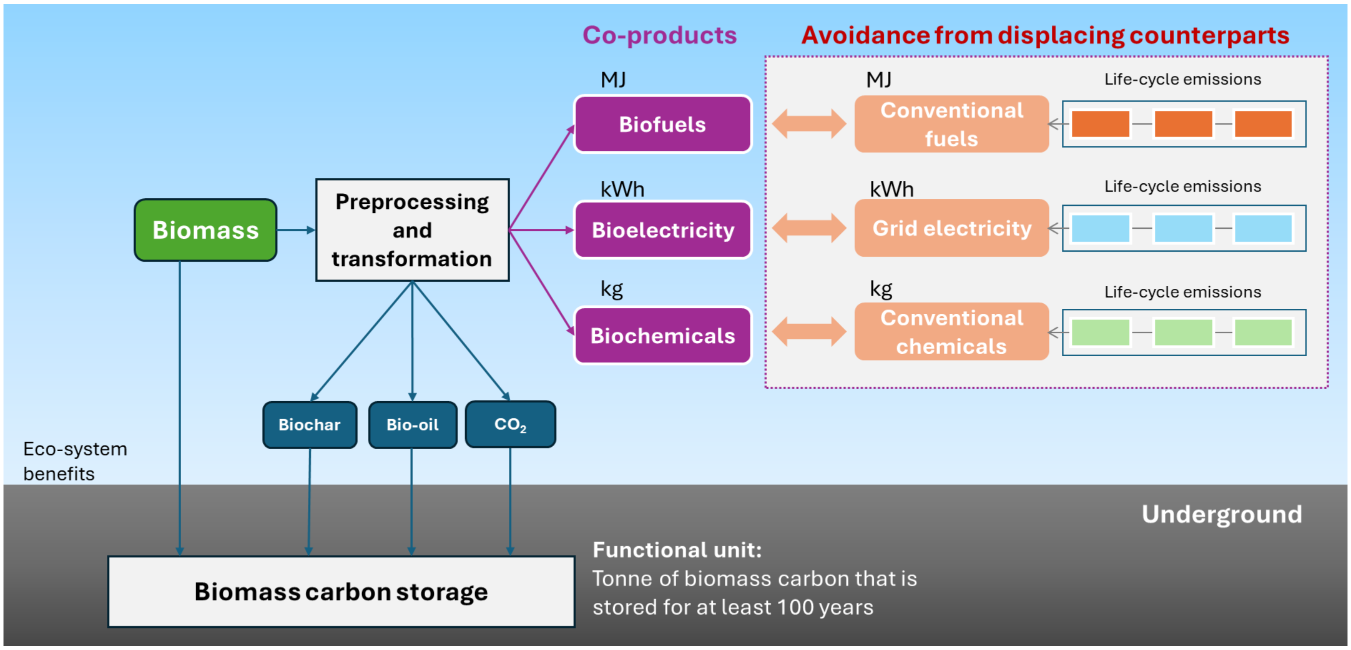


Figure 4. Co-Product Management of BiCRS LCA, Using the BECCS Technology Spectrum as An Example.

For BECCS technologies, an allocation approach (especially a mass- or energy-based process-level allocation that differentiates physical relationships or the purposes of the processes) could also be applied to separate the environmental impacts of biomass carbon removal from those of the bioenergy co-products. In this case, biomass carbon removal will adopt the functional unit recommended in Section 3.1.2, while an energy-based functional unit such as per MJ of biofuel or per kWh of electricity should be applied to the bioenergy co-products.

Note that certain LCA may focus on evaluating the environmental impacts of energy products with the functional units of MJ biofuel or kWh electricity. In these cases, the system expansion with displacement method could be applied to consider the carbon removal as emission reductions for bioenergy production. For example, CO_2

captured and stored during corn ethanol-derived jet fuel production can provide emission reductions of 34 g CO_2e/MJ (Yoo et al. 2022). Similarly, electricity with CO_2 capture may have a lower carbon intensity compared to the case without CCS when biomass carbon removal is considered a credit that is applied to the bioenergy products.

Although the selection of the functional unit would depend on the goal of each LCA, the same emission reduction benefits should not be accounted for twice. If the emission reduction impact of CCS is accounted for when calculating the carbon intensity of biofuels, it should not be reported as additional emission reduction or removal somewhere else.

Best practices

- See Section 3.4 for best practices for co-product management.
- For co-benefits such as soil improvement or waste reduction, it is recommended that they are included and discussed at least qualitatively if relevant to the system, e.g., when agricultural residues, food waste, or forest residues are used as feedstocks.
- Co-benefits are highly dependent on such local conditions as soil type, climate, and socioeconomic conditions. Ensure that the LCA reflects regional specifics where the BiCRS system is implemented.

3.6 Interpretation

Background

Interpreting LCIA results is a critical step in the LCA of BiCRS systems. Proper interpretation ensures that the results are meaningful, actionable, and scientifically valid.

In LCA, negative emissions generally arise from one of two situations:

1. Removal of the emission species from an environmental compartment (e.g., biomass uptake of atmospheric CO_2 during photosynthesis). Note the removal of an emission from one compartment does not imply permanence of storage or avoidance of future re-emission. Those attributes, along with shifts to other environmental compartments, should be accounted for in separate processes within the system boundary.
2. Avoided emissions associated with the production of a product by another means (e.g., when using system expansion with displacement to manage co-products) or by alternative management practices of wastes.

The interpretation of these two situations is quite different (Tanzer & Ramírez, 2019). In the first scenario, the emission of interest is physically removed from an environmental compartment. The exact amount is defined by the functional unit for the system of study. If the functional unit is scaled up, the corresponding physical removal is also scaled up along with any downstream fate of the emission.

In the second scenario, the negative emissions do not represent a physical removal, but rather an avoidance of emissions by opting for one method of production over another. When an LCA includes a displacement or avoided emissions credit, the implication is that this displacement occurs fully in the market (i.e., the co-product displaces 100% of another product, meaning no additionality occurs). Further, this approach is specific to study goal and scope for the system of interest.

Relevance to BiCRS

The differentiation of removed and avoided emissions is of critical importance for assessing the efficacy of potential CDR technologies. When evaluating CDR pathways, one of the key metrics will be the amount of net negative emissions relative to an atmospheric rather than technospheric baseline achieved by the technology. Due to the inclusion of material and energy inputs in the LCA, and their associated supply chain emissions, the net portion of the net negative emissions refers to the quantity of CO_2 actually removed after accounting for positive emissions that also occur to support the BiCRS process.

Certain types of biomass (e.g., residue biomass or organic waste resources) may undergo typical management practices when they are not sourced for a BiCRS technology. When such biomass sources are used in a BiCRS technology, the net GHG emissions or net carbon storage from regular management practices of such biomass present avoided net GHG emissions or foregone net carbon storage. These are commonly referred to as alternative fate or “counterfactual” impacts.

Best practices

- For systems with co-products, when system expansion is used to manage multiple outputs, report avoided emissions and atmospheric removals separately in the results
- When the study includes avoided emissions associated with an alternative fate of the biomass they should be represented with distinct and separate accounting for transparency.
- If a BiCRS facility includes capture of CO_2 from on-site fossil fuel combustion or other non-atmospheric CO_2, separately report that amount from the atmospheric CO_2 captured
- Assess the completeness of the LCA. Ensure that the LCA covers all significant stages of the life cycle of a BiCRS system within the defined system boundary and verify that data for all life cycle stages is not missing or excluded.

3.7 Sensitivity and uncertainty analysis

Background

LCA is a data-intensive framework, often requiring a well-characterized system with process details to derive representative and complete LCA results. Uncertainty and variability in these decisions manifest from (1) parameter uncertainty, (2) uncertainty of modeling methodologies for calculations of specific impact categories and for addressing co-products, alternative fates, indirect effects, etc. whenever applicable, (3) scenario uncertainly, (4) spatial variability, and (5) temporal variability. Parameter uncertainty can manifest from variability in the underlying population from which data is sampled, either measured or observed (Bamber et al. 2020). Model uncertainty stems from the mathematical relationships used in the LCA model calculations as well as applications of models for producing data for inventories and impacts assessment methods (Bamber et al. 2020). Finally, scenario uncertainty pertains to choices that are made to represent extensions of applications of the system under study, including geographic, technological, and temporal. All LCAs have some combination of these uncertainties, but the importance of each is highly dependent on the application and the system of study.

Various approaches can be used to manage and better understand the implications of the underlying uncertainty and variability in a model:

- Sensitivity analysis: Identifying key parameters that influence the LCA results the most via a hotspot analysis and then altering the values of such parameters within reasonable ranges to assess the resulting changes in the model results. Sensitivity analysis provides insights into future data collection, characterization, and representation. When varying specific parameters, it is important to understand possible causal relationships between the parameter and others and make sure that such causal effects are maintained and avoid arbitrary responses to changes in the parameters that may violate such causal relationships.
- Scenario design: A robust approach for providing insights about how the likely sources of uncertainty will impact the study results over a broad range of assumptions. So-called “bounding scenarios” can be used to understand the potential best- and worst-case impacts of a potential system. No likelihood is prescribed to either extreme, but they can be used to inform refinement in design as a technology moves towards commercialization. In addition, for BiCRS systems that need to address impacts from alternative fates and/or indirect effects such as ILUC related to choices for the biomass feedstock and feedstock sourcing at scale, a

well-designed scenario analysis that considers likely alternative fates and scenarios of indirect impacts such as ILUC provides insights into a possible range of environmental impacts related to such issues.

- Simulation: The overall uncertainty in model results can be evaluated by implementing stochastic simulation of model parameters and data based on the probabilistic distribution of their values (Thaneya et al. 2024). This approach yields a probabilistic representation of the model results. The challenge of this approach is that it requires a statistically significant sample size of data that reasonably reflects operational conditions of the system and thus allows for robust characterization of a statistically meaningful distribution that describes the likelihood of occurrence of events related to specific parameters. In addition, the interpretation of results, especially for early stage and uncertain technologies where robust underlying parameter distributions do not exist or are not well understood, may imply more certainty than exists. The results are highly dependent on the underlying distributions chosen or characterized to represent the model parameters.

Relevance to BiCRS

Given the wide spectrum of BiCRS technologies that may manifest unique process designs and may still be early-stage in development, robust and large-scale operating data may be unavailable and uncertainty in the representation of BiCRS in an LCA is likely to exist. There may be significant uncertainty and variability in process parameters, inventory data, and modeling choices for early-stage BiCRS technologies.

Best practices

- Conduct hotspot analysis to identify key parameters and conduct sensitivity analysis of the key parameters considering reasonable ranges of variability and possible causal relationships with other parameters.
- Given well-characterized data that reflect actual operational conditions that may vary within normal ranges including downtime, perform stochastic simulation-based uncertainty analysis to propagate uncertainty/variability associated with multiple key parameters within the system boundary of a BiCRS system.
- Use of scenario analysis and consider bounding scenarios to inform key decision points.
- Sensitivity analysis should be performed for key parameters in modeling that estimates ILUC and terrestrial carbon leakage effects, including for assumptions such as temporal and spatial scales.

4. LCA best practices for dedicated BiCRS and BECCS technologies

4.1 LCA best practices for dedicated BiCRS

4.1.1 System boundaries and process parameters

As explained in Section 3.1.1, the cradle-to-grave system boundary includes all life-cycle processes along the supply chain, and impacts from alternative fates. For BiCRS, the system boundary includes biomass production, biomass collection, biomass transportation, conditioning, pretreatment, and/or conversion, biomass carbon storage, and leakage from biomass carbon storage. All direct and indirect impacts associated with the energy/material inputs to the system should be accounted for.

Figure 5 presents the generic system boundaries of the dedicated BiCRS systems (e.g., biomass burial, biochar applied to agricultural fields, and bio-oil injection). These technologies are intended to store carbon from biomass, albeit other potential co-benefits such as ecosystem benefits. If the biomass comes from new rotations of short rotation woody crops and/or short rotation forestry dedicated for BiCRS (i.e., all of the biomass from the rotations goes to carbon removal), there would be no alternative fates. However, outside of such dedicated rotations, management practices or utilization purposes would exist for residue/waste biomass, or biomass with other potential end uses. For waste biomass, diversion of the biomass to BiCRS means that those alternative fates would be avoided. Therefore, when accounting for the impact of BiCRS from waste biomass, avoided emissions from alternative fates and/or foregone carbon sequestration (F) should be included. For example, if forest residues are not collected for biochar production, these can be left on the ground to decay over time, generating CO_2 and CH_4 emissions, while a portion of carbon could contribute to the accumulation of soil organic carbon. On the other hand, forest residues could be burned or used for other productive applications. These alternative fates may vary from case to case and their associated emission and environmental impacts need to be considered. Note that careful consideration should be given to the selection of the alternative fates conditions, including consideration of how these fates may change over time or in different circumstances. As another example of residue biomass, corn stover may undergo typical sustainable management practices that retain certain amounts of the crop residue in the field to maintain soil fertility. The sourcing of corn stover for BiCRS purposes needs to address whether the level of stover removal influences the typical residue management practices and if so, the environmental impacts.

In addition, leakage effects (G), if applicable, such as ILUC and terrestrial carbon impacts, should be accounted for.

The main objective of dedicated BiCRS is to store biomass carbon underground. To quantify the life cycle environmental impacts of performing this function, the best practice of the dedicated BiCRS LCA is to apply the functional unit defined in Section 3.1.2, i.e., per tonne of biomass carbon that is stored for at least 100 years. The LCA results include estimated net CO_2e per tonne of biomass carbon stored for at least 100 years.

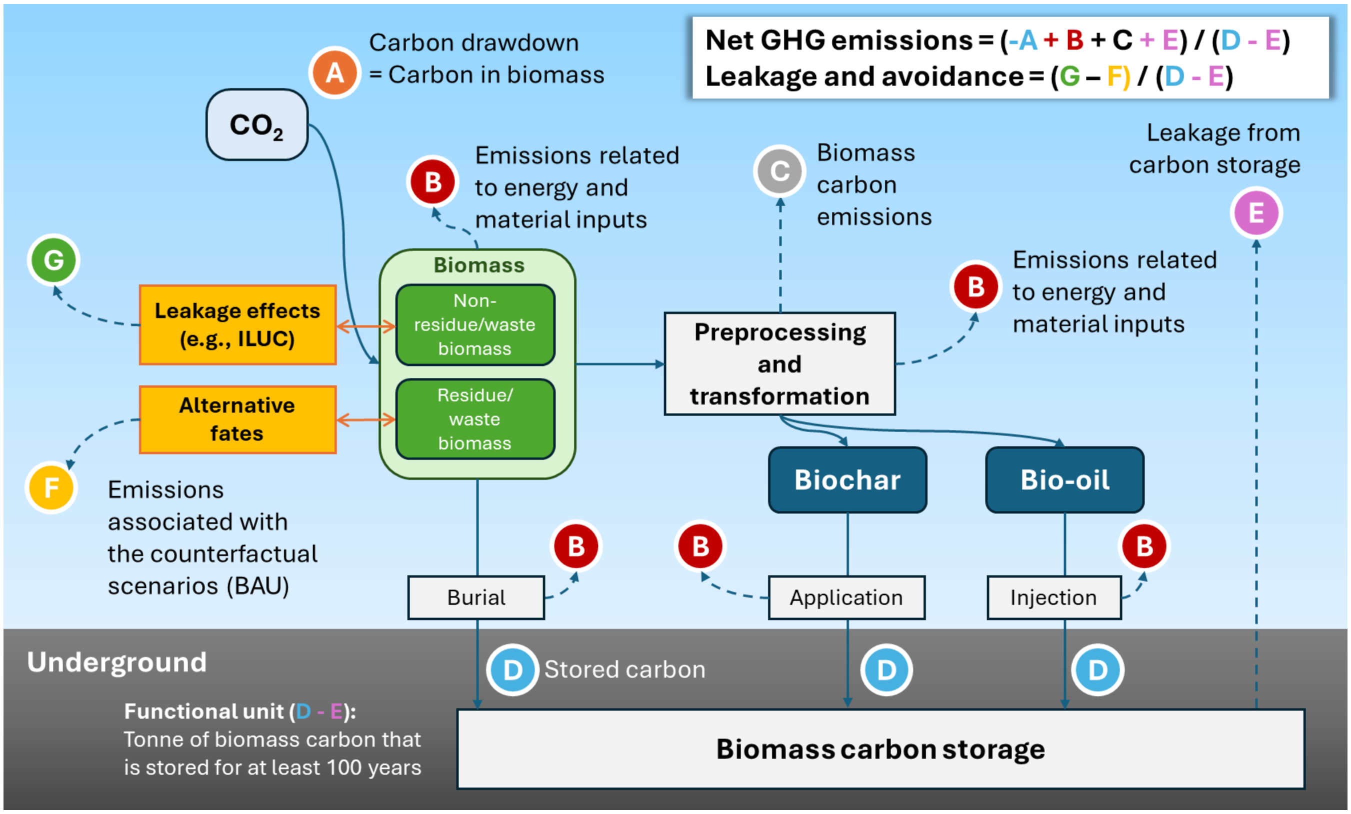


Figure 5. Schematic of A Cradle-to-Grave LCA System Boundary of Dedicated BiCRS and Key Processes.

Regardless of the eventual physical form(s) of the biomass carbon that is stored durably, all biomass carbon comes from the uptake of CO_2 from the atmosphere via photosynthesis. Therefore, carbon in biomass is equal to carbon drawn down from the atmosphere (A). However, biomass production may have consequential effects that may include avoided impacts from alternative fates (F) and leakage effects (G). These impacts differ from the net GHG emissions that account for the overall direct emissions of the BiCRS system. The best practice is to report such consequential emissions separately.

All the emissions associated with energy and material inputs used for biomass production, sourcing, and logistics, whichever applicable (B) should be accounted for. For example, if fertilizers are used for biomass production, emissions from fertilizer production, transportation, and application should be accounted for. Depending on the sources of the biomass, (B) may be attributed to other main products and co-products if the biomass is residue or waste biomass. For example, corn stover is considered residue biomass that remains after the main crop, i.e., corn is produced and harvested. With a marginal approach, corn stover does not share any emission burdens from producing and harvesting corn and all the emissions from biomass production are attributed to corn. Meanwhile, the residue feedstocks are only responsible for the emissions related to collection, transportation, and preprocessing. As the corn stover-based BiCRS technologies scale up which may drive the demand for corn stover, making it marketable commodity that may influence the farmer's decision and farming practices, an alternative allocation approach may be considered to allocate part of the upstream emissions during corn farming to the stover as a feedstock for a BiCRS technology.

When the biomass undergoes preprocessing and transformation to the finished forms of biomass carbon, e.g., biochar or bio-oil for storage, some biomass carbon could be lost in the form of intermediate flue gas and/or solid or liquified waste (C). In addition, the biomass preprocessing and transformation processes may require additional energy and material inputs, which may incur associated emissions (B).

Here, the mass and energy balance of the preprocessing and transformation processes should be collected to evaluate the emissions and other environmental impacts. The biomass carbon loss (C) can be estimated using a carbon balance approach, i.e., the difference between the carbon in the biomass and the carbon in the finished carbon products represents (C).

On the other hand, other inputs such as fossil natural gas and electricity used for converting biomass into biochar or bio-oil contribute to net GHG emissions. Using the method explained for estimating (B) for biomass production, emissions related to energy and material inputs for the conversion process can be estimated. Thus, the energy and material inputs need to be collected with respect to the production of biochar and/or bio-oil.

The CO_2e of the biomass carbon storage (D) can be estimated based on the amount of biomass-based materials that are stored and the carbon contents (%) of the materials. This process may also require energy and chemicals (e.g., liquid pumping, excavation, etc.) leading to associated emissions (B), which can be estimated based on the energy and chemical consumption and the associated emissions factors.

In order to estimate the durably stored carbon, any carbon leakage from the carbon storage (E) should be accounted for. The carbon leakage should include all expected future leakage from the storage or indirect emissions associated with any activities to maintain/operate the carbon storage over a period of at least 100 years. Since the carbon leakage cannot be measured in advance during the LCA process, a detailed geocellular model simulating the properties of the biomass carbon storage formation and the overlying layers is needed to estimate the degree of potential, long-term carbon leakage over the timeframe.

Taking into account the above emission sources and sinks, the net CO_2e of a dedicated BiCRS technology is calculated with the explicit biogenic carbon accounting approach (see Appendix A2). This method accounts for the initial carbon drawdown during biomass production (A), GHG emissions related to energy and material uses (B), biogenic carbon emissions/losses during biomass preprocessing and transformation (C), which offset A, and biomass carbon leakage during carbon storage (E), using the net biogenic carbon storage (D–E) as the functional unit.

In addition, leakage and emission avoidance that may include GHG emission impacts of alternative fates (F) and indirect GHG emissions such as ILUC (G) are considered but reported separately.

4.1.2 A dedicated BiCRS LCA example

Here is one example of dedicated BiCRS LCA using generic conditions of pyrolysis of woody biomass for bio-oil and biochar production, followed by biooil injection and biochar application. Figure 6 presents the system boundary together with the carbon/mass flows collected from the literature. Note that the values in this example are for an illustrative purpose only; different pyrolysis conditions using different types of feedstocks would lead to different bio-oil and biochar yields with different characteristics. This example applies the explicit biogenic carbon accounting approach.

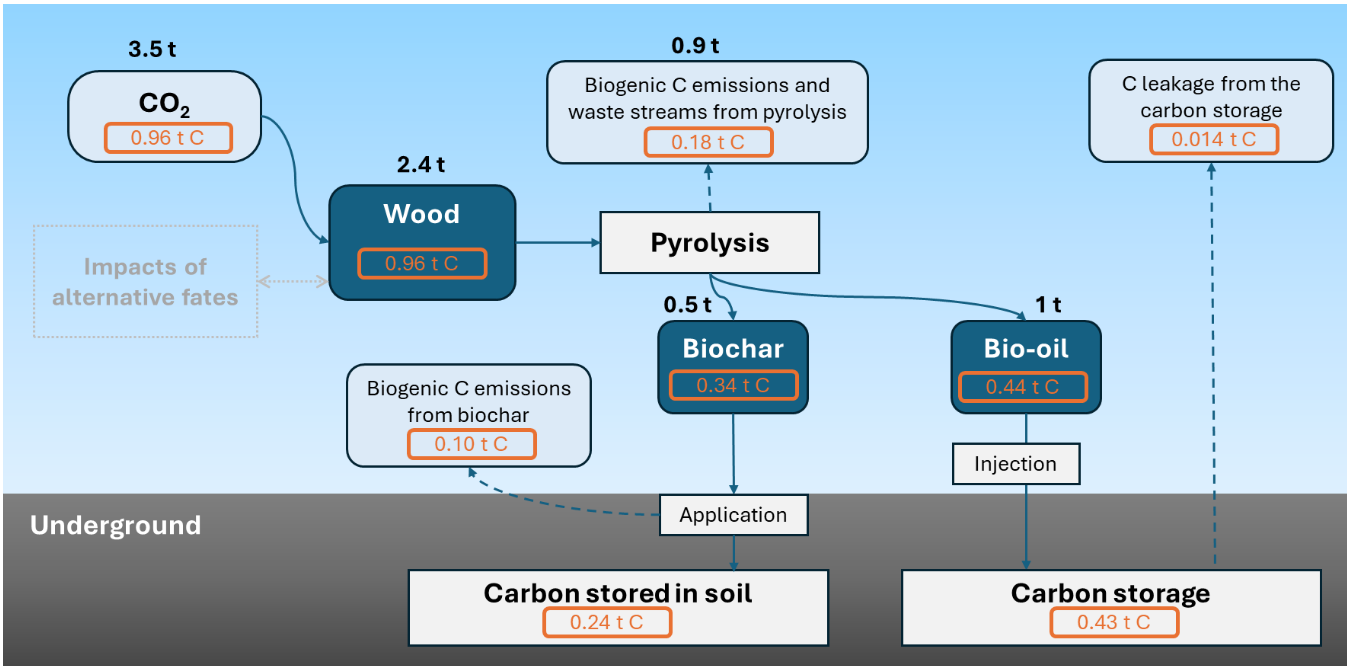


Figure 6. Mass of Biogenic Carbon Flows of An Example Case for the Dedicated BiCRS System: Woody Biomass Pyrolysis for Biochar and Bio-Oil Production and Storage. Note: For Simplicity's Sake, Fossil Emissions Are Not Included in This Figure But Are Accounted for in the Following Text Example.

In this example, 2.4 metric tonne (t) of woody biomass is used to generate 1 t of bio-oil and 0.5 t of biochar. Then, biochar is applied to soil and bio-oil is injected into underground storage. First, the amount of carbon storage (before considering any other emissions) can be estimated using the carbon contents of bio-oil and biochar. Here, with a 44% carbon content, carbon in bio-oil is estimated at 0.44 t. Similarly, carbon in biochar is estimated at 0.34 t (with a 68% carbon content) in 0.5 t of biochar.

Only a portion of biochar applied remains in soil over a timeframe of 100 years or longer. The rest would be decomposed as CO_2 and released back to the atmosphere. Here, we consider that 70% of the carbon in biochar remains in soil after 100 years (Woolf et al. 2021), which means 0.1 t of carbon (0.34 t × [1 – 70%]) applied to soil is released (0.37 t CO_2e). Depending on the conditions of the storage system, there is a risk of carbon leakage, which may release carbon back into the atmosphere. In this example, we considered 2% of the biomass carbon storage is released over 100 years. Therefore, the total carbon leakage from biochar application and biooil injection in this case is 0.014 t C ([0.34 × 70% + 0.44] × 2%). This is the carbon leakage represented as (E) in Figure 5, which negates biomass carbon storage benefits. The remainder of the biochar carbon and biooil carbon that is durably stored is estimated at 0.66 t C or 2.44 t CO_2e. These are presented as (D) in Figure 5.

Other than the mass/carbon flows, we also need to consider the impact of the use of energy and material inputs for the entire supply chain of this system. First, all emission burdens of the woody biomass production should be accounted for unless the biomass feedstock is a waste feedstock (e.g., forest residues). In R&D GREET 2023 Rev1 (Argonne National Laboratory 2023), clean pine feedstock production including energy/chemical uses during farming plantation, collection, transportation, storage, and preprocessing leads to 0.15 t CO_2e/dry t pine. Considering the moisture content (15%) and the amount of woody feedstock (2.4 t) used for 1 t bio-oil and 0.5 t biochar production, the emissions for feedstock production become 0.31 t CO_2e. If forest residue (residue feedstock) is used instead, emissions associated with feedstock production would become much smaller because the system boundary starts from the residue collection.

Similarly, the pyrolysis process requires energy/material inputs. In this example, we assumed that electricity of 186 kWh/t bio-oil is the only energy requirement for the pyrolysis stage, which translates to 0.08 t CO_2e using the carbon intensity of the current U.S. grid mix (i.e., 440 g CO_2e/kWh). Although biochar application and bio-oil injection would require additional energy, the contribution to the net GHG emissions may be marginal. Considering biomass carbon storage (D), biomass carbon reversal (E), and the emissions associated with energy/material inputs across the cradle-to-grave life cycle stages, net GHG emissions without any applicable leakage or avoidance are estimated at -0.84 t CO_2e. Table 3 shows the summary of the emission contributions to the net GHG emissions of bio-oil injection and biochar application using woody biomass pyrolysis.

Table 3. GHG Emissions and Biomass Carbon Removal to Calculate the Net GHG Emissions of the Example Dedicated BiCRS System. The categories represent those marked in Figure 6.

Category	Item	Carbon (t)	CO_2 equivalent (t)
A	C captured by woody biomass = C in woody biomass	0.96	3.52
B	Emissions for feedstock production	-	0.31
	Emissions for the pyrolysis process	-	0.080
C	Biogenic C emissions	0.18	0.66
D	C in bio-oil = Injected C	0.44	1.61
	C in biochar = Applied C	0.34	1.25
E	C reversal (biochar)	0.10	0.37
	C reversal (bio-oil)	0.0088	0.0032
F	Impacts from alternative fates		To be determined case by case
G	Indirect effects such as ILUC		To be determined case by case
Net GHG emissions = (-A + B + C + E) / (D – E)		**-**	**-0.84 t CO_2e/t biogenic carbon removal (excluding potential leakage or avoidance)**
Leakage and avoidance = (G – F) / (D – E)			**To be determined case by case**

Note that the impact of alternative fates (F) may need to be accounted for when residue or waste feedstock is used, as discussed in Sections 3.1.1 and 3.5.2. For example, if forest residue that is not purposely produced is used to produce bio-oil and/or biochar, the BAU management practices in place for forest residues may be avoided. Forest residues may be left on the ground, which may decay over time while a portion of carbon remains in soil or it may be sourced for energy production (e.g., bio-electricity or heat). Thus, depending on where the forest residue is sourced and which BAU management or utilization scenario is diverted from, the impacts from alternative fates may vary significantly, potentially varying the LCA results significantly. Therefore, it is recommended to identify project-specific alternative fates and quantify the associated emissions and other environmental impacts.

4.2 LCA best practices for BECCS

This section elaborates on the best practices for BiCRS technologies discussed in Section 3 and addresses unique issues associated with BECCS systems, such as multifunctionality and process parameters for emerging technologies in the BECCS space. It also discusses process sensitivities that may influence the results substantially.

4.2.1 System boundaries and process parameters

Figure 7 presents a generic, cradle-to-grave system boundary of a BECCS system. Here, the dual purposes of carbon storage and bioenergy production need to be addressed following best practices of co-product management discussed in Section 3.4.

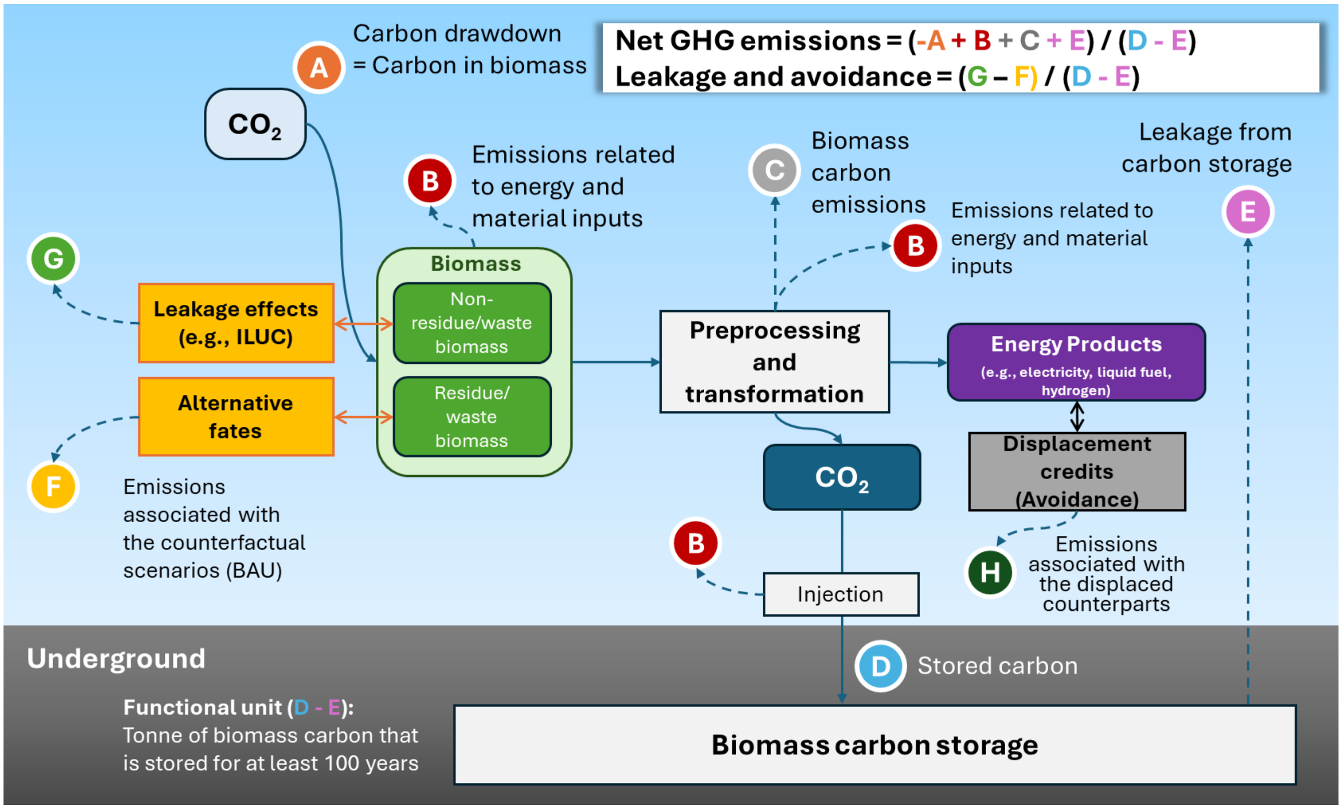


Figure 7. Schematic of a Cradle-to-Grave LCA System Boundary of BECCS and Key Processes.

As stated in Section 3.1.1, the cradle-to-grave system boundary is recommended to address BECCS pathways. Key processes to consider include the supply chain of biomass production; harvesting/sourcing, processing, and transportation to a BECCS facility; transformation/conversion to bioenergy; and CCS. In addition, impacts from alternative fates associated with residue and waste biomass or biomass from existing production systems without regeneration may need to be addressed. Furthermore, indirect effects such as ILUC impacts for certain biomass feedstocks such as dedicated biomass in newly converted land need to be addressed. That said, BECCS pathways entail some unique stages, which include energy conversion stages, CO_2 transport, and geologic storage.

Biomass conversion

The type of BiCRS conversion technology affects not only the inventory details and process parameters (such as energy penalty) but also the co-products. Moreover, it determines the design of the CO_2 capture process and the amount of captured CO_2. BiCRS pathways that produce bioliquids (such as Fischer-Tropsch fuels and ethanol) may have a relatively high (>95%) CO_2 concentration of the flue gas, presenting opportunities for carbon capture and storage. That said, the energy penalty of capturing flue gas CO_2 associated with bioelectricity pathways tends to be greater because of low-to-medium purity CO_2 streams (e.g., approximately 10% for combustion and 40–60% for gasification). Accordingly, the best practices for BECCS include:

- Develop a complete life cycle inventory of the process energy and material balances of the BECCS system, including biomass carbon conversion efficiency of producing bioenergy and the quantity of the process CO_2 stream that is captured and stored.
- Document the purity, temperature, and pressure of the process CO_2 stream, along with any relevant impurities affecting CO_2 capture.
- Clarify the CO_2 capture efficiency and the energy and material requirements of the CO_2 capture technology.

- Apply the explicit biogenic carbon accounting approach.

CO_2 transport

The mode of CO_2 transport may be rail or ship for demonstration projects and is likely to be pipelines for commercial-scale projects. A limited number of projects may not require extensive transport infrastructure in case a particular CO_2 source is co-located with geologic sinks. The type of energy source and its associated GHG intensity would affect life-cycle emissions. The mode of CO_2 transport would therefore be a function of the scale of the project and the source-sink distance.

The interpretation of LCA results should clarify whether a pipeline is tied into an existing pipeline network (i.e., CCS cluster) or if it exists as a standalone feature. We recommend the following best practices for CO_2 transport:

- Develop the life cycle inventory that includes the transport mode(s) and the associated distance for transporting the CO_2 source partially or entirely from the BECCS facility to the geologic sink.
- If pre-existing infrastructure is being used and its life cycle burdens are considered “amortized”, it should be clearly noted with references.
- LCI data for pipeline transportation should entail the energy requirement of booster pumps, if needed, in kWh of electricity per ton CO_2-mile.

Geologic CO_2 storage

Geologic storage of CO_2 may take place in a variety of formations, such as saline aquifers, oil/gas, and coal formations or basalts, with the dedicated purpose of CO_2 storage. Note that CO_2 storage that takes place in oil and gas reservoirs for the purposes of enhanced hydrocarbon recovery is out of the scope of this best practices document. Although geologic CO_2 storage has been considered safe and past work has assumed a 100% storage rate, leakage from the storage should be estimated. First, there is a considerable variation in the leakage rate depending on the types of geological storage such as offshore and onshore reservoirs. Second, since leakage from storage could take place over a long period, the cumulative leakage rate may exceed the estimated leakage rates based on optimal conditions. Even in the case of a well-regulated reservoir, sensitivity analysis may be carried out to account for leakage risks due to unexpected disruptions. Several past LCAs have not considered the influence of sink properties on the LCI. Some studies have excluded this stage entirely from the system boundary, while others have used a default inventory value for such stages. While this was reasonable for initial studies, there has been an increasing focus on contextual explicitness. The United States has wide variability in the reservoir properties. As an example, the depths of CO_2 storage in reservoirs being considered currently range from 1,200 m to 4,000 m (Singh et al. 2021). As such, regional and geologic specificity would enable more accurate LCAs in this domain. Practitioners are advised to use site-specific leakage rate based on field data availability.

Finally, CO_2 injection in several reservoirs may result in production of brackish or saline waters, which should be considered a part of the BECCS system boundary. These waters may be reinjected or, in other cases, be treated for beneficial reuse. The disposal and treatment strategy are dependent on multiple conditions (e.g., produced water quality, availability of desalination technologies, regional water stress). In turn, this determines the energy consumption and life cycle water availability. Reports by the IEA and the IPCC, among others, have noted that the treated produced water may partially or fully offset the upstream water consumption for CCS processes (Clarke et al. 2022).

In view of these factors, following are best practices for LCA of the CO_2 storage component:

- Develop a complete LCI of the energy and chemical requirements for geologic storage of the CO_2, including ancillary processes such as treatment, conditioning, separation, etc.

- Estimate the CO_2 leakage rate based on reservoir parameters such as depth, porosity, permeability, and thickness of the reservoir. In addition, the estimate should consider whether the storage potential and injectivity criteria of the geologic sink could sufficiently accommodate the scale of the BECCS project.
- The LCA should discuss broad environmental impacts and co-benefits that may be relevant, such as water consumption, besides the climate impacts.
- The NETL gate-to-grave assessment of saline aquifer storage of CO_2 (Littlefield et al. 2013) can serve as a model for addressing this portion of the life cycle.

The wide spectrum of BECCS technologies may present unique aspects, especially the physical form of the biogenic carbon. Besides biogenic CO_2 from the BECCS processes, liquid or solid biogenic carbon may be targeted for long-term storage, e.g., biochar produced with pyrolysis oil. Therefore, reservoir designs, operations, and maintenance may entail significant nuances that affect the development of the LCI, estimation of the durability of the biogenic carbon storage, and potential co-benefits and broad environmental impacts. We refer LCA practitioners and project operators to Section 3 for general recommendations and to this Section to customize the LCA practices following the specific best practices on related issues.

Multi-functionality

At a minimum, a BECCS system has two functions: bioenergy production and biogenic carbon storage. Depending on the goal statement of the LCA, one or more functional units may be defined to address the net CO_2e of the bioenergy production and biogenic carbon storage. The functional unit could be selected as 1 kg CO_2 (or similar) removed and durably stored in geologic sinks or 1 MJ (or similar) bioenergy production.

In the case of the former, the bioenergy product(s) may be considered a co-product. As discussed in Section 3.4, two co-product management methods (the system expansion with displacement method and allocation at the process level) can be applied. With the system expansion with displacement method, two scenarios present a decision-making point: (1) the displacement credits of the bioenergy co-product(s) will be entirely attributed to the biogenic carbon storage on a per ton of biogenic carbon storage basis; and (2) the biogenic carbon removal and storage presents a displacement credit that will be entirely attributed to all the bioenergy product(s) on a per-MJ-of-bioenergy production basis. The LCA goal should be considered to guide this decision making.

With the process-level allocation method, the mass of biomass feedstock going into bioenergy production and the biogenic carbon stream(s) that are removed for durable storage can serve as the allocation basis. Following this allocation approach, LCA results per MJ of bioenergy and per tonne of biogenic carbon removed and stored can be generated separately.

In summary, we suggest the following best practices for multi-functionality for BECCS:

- Functional unit selection should address the goal statement of the LCA, i.e., whether it is meant for comparison of the biogenic carbon removal and bioenergy production separately, or focusing on a main service, which could be either the bioenergy production or biogenic carbon removal and storage.
- When the primary goal is to address the biogenic carbon removal and storage, the primary functional unit to serve this purpose is per tonne of biogenic carbon removal and storage. In this case, displacement credits from the energy co-products should be evaluated and documented. The assumptions regarding current and any expected future energy products being displaced along with their life-cycle emissions of the counterparts should be clarified and justified. It is recommended to conduct a sensitivity analysis to compare the net CO_2e of biogenic carbon removal and storage with and without the displacement credit of the co-produced bioenergy product(s).
- In BECCS pathways with multiple energy products, the co-product handling approach selected to address the multiple bioenergy products (e.g., energy-based allocation, mass-based allocation, or market value-based

allocation) should be clearly mentioned to avoid ambiguity. The energy-based allocation method is recommended per ISO standard discussed in Section 3.4.

4.2.2 A BECCS LCA example

Bio-electricity generation with CCS

Here we present biomass-based electricity and heat generation, followed by biogenic CO_2 capture and geologic storage as an example of a BECCS system. Figure 8 presents the system boundary together with the biogenic carbon and bioenergy flows. Similar to the example in Section 4.1.2, the values in this example are for illustration purposes only.

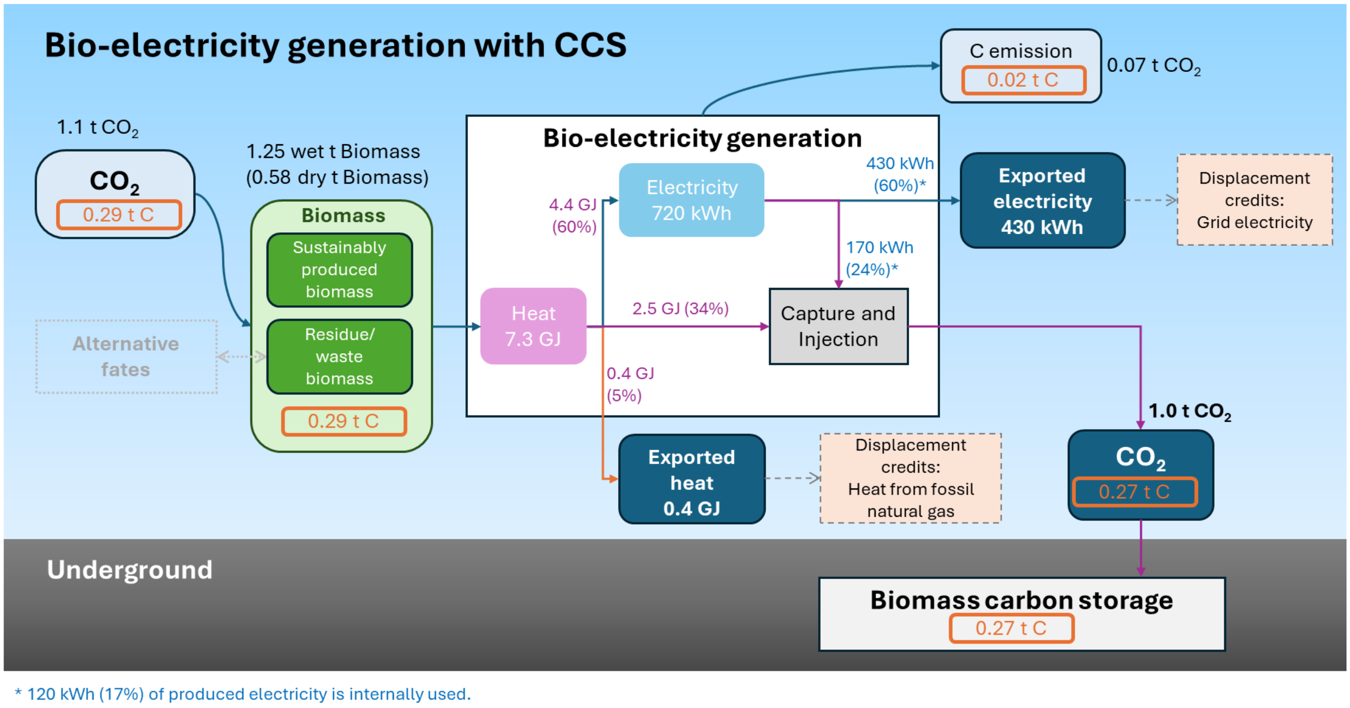


Figure 8. Biogenic Carbon and Bioenergy Flows of Biomass-Based Electricity and Heat Generation with CCS. Note: Fossil Emissions Are Not Included for Simplicity But Are Accounted For in the Text.

Goal: To estimate the life cycle GHG emission impacts of a biomass-based electricity and heat production facility integrated with a CCS system.

Functional unit: Two functional units could be considered to quantify the life cycle GHG emissions of the dual services from a BECCS, i.e., biogenic carbon removal and bioenergy production: (1) biogenic CO_2 storage based (e.g., 1 kg biogenic CO_2 stored in geologic formations); and (2) bioenergy production based (e.g., 1 kWh electricity). Regardless of the choice of the functional unit, two co-product management methods (the system expansion or displacement method and the process-level allocation method) could be applied to estimate the life cycle GHG emissions of biogenic carbon removal and bioenergy production, respectively.

We start with an illustration of quantifying the life cycle GHG emissions of biogenic carbon removal and storage with a function unit of 1 kg of biogenic CO_2 removal and storage from the BECCS system, as shown in Figure 8, using the system expansion and the process-level allocation methods, respectively.

In this example, 1.25 wet tonne (t) or 0.58 dry t of biomass that contains 0.29 t of biogenic carbon is fed to a combined heat and power (CHP) unit. The CHP unit generates 7.3 GJ of heat, of which 4.4 GJ is diverted to generation of 720 kWh of electricity, 2.5 GJ is diverted to satisfying heat demand of CCS, and 0.4 GJ is exported. Of the 720 kWh electricity, 170 kWh is diverted to satisfying the electricity demand of CCS, 120 kWh is used internally, and 430 kWh is exported to the grid. The electricity and heat production generates about 1.07 t biogenic CO_2 emissions, of which 1.0 t is captured and stored with a capturing efficiency of 95%. Under a well-regulated sink, the biogenic CO_2 is assumed to be stored durably over 100 years or longer (Alcalde et al. 2018).

In addition to the carbon and bioenergy flows, we consider the energy and material inputs for the entire supply chain of this system. First, all emission burdens of the biomass production are accounted for. For woody biomass (pine wood), the CI of feedstock production is estimated at 66 kg CO_2e/dry t feedstock including pine production and transportation using the default assumptions in R&D GREET 2023 Rev1 (Argonne National Laboratory 2023). For residues/waste biomass, the impact associated with residues/waste feedstock collection could be relatively smaller (37 kg CO_2e/dry t forest residue). In this case, however, impacts of alternative fates associated with the conventional residue/waste management should be evaluated separately and included as avoided emissions (or emission credits).

For electricity generation, we assumed that it is self-sustainable using biomass only. However, if the power generation process requires energy/material input, these process GHG emissions should be included. CO_2 transportation and injection would require additional energy and must be reported separately from biogenic carbon uptake. Table 4 shows the summary of the emission contributions to the net GHG emissions of this BECCS system, the categories represent those marked in Figure 8.

Table 4. Net GHG Emissions of 1 t of Biogenic Carbon Capture and Storage in the Example BECCS System, Using the System Expansion Approach.

Category	Item	Carbon (t)	CO_2 Equivalent (t)
A	Carbon in biomass	0.29	1.06
B	Emissions for feedstock production	-	0.038 (pine)
C	Biogenic CO_2 emissions escaped from flue gas	0.020	0.073
D	Captured and injected biogenic CO_2 emissions	0.27	0.99
E	Physical leakage from biogenic CO_2 storage	0	0
F	Impacts of alternative fates		To be determined case by case
G	Leakage such as ILUC		To be determined case by case
H	Avoidance (displacement credit) of 430 kWh grid electricity	-	0.19
	Avoidance (displacement credit) of 0.4 GJ of heat from fossil natural gas	-	0.035
Net GHG emissions = (– A + B + C + E) / (D – E)		**-**	**-0.96 t CO_2e/t biogenic carbon removal (excluding potential leakage or avoidance)**
Leakage and avoidance = (G – F – H) / (D – E)			**To be determined case by case**

With a system expansion method, biomass-based electricity that is exported (430 kWh) to grid is assumed to displace the U.S. average grid electricity with a CI of 0.44 kg CO_2e/kWh. This translates to a displacement credit of 189 kg CO_2e. Similarly, co-produced heat of 0.4 GJ that is exported is assumed to displace fossil natural gas-derived heat that has a CI of 87 kg CO_2e/GJ heat (considering an 80% boiler energy efficiency), which leads to a displacement credit of 35 kg CO_2e. Table 5 summarizes the breakdown of the calculation of net GHG emissions and CI of 1 t of biogenic CO_2 capture and storage, using the system expansion method.

Table 5. Net GHG Emissions of the CCS, Exported Electricity, and Exported Heat, respectively, of the example BECCS system using the process-level allocation method. The categories represent those marked in Figure 8.

Category	Items	Carbon (t)	CO_2 equivalent (t)
A	C captured by biomass = C in biomass	0.29	1.06
B	Emissions for feedstock production	-	0.038 (pine)
C	Biogenic CO_2 emissions escaped from flue gas	0.020	0.073
D	Captured and injected biogenic CO_2 emissions	0.27	0.99
E	Physical leakage from biogenic CO_2 storage	0	0
F	Impacts of alternative fates		To be determined case by case
G	Leakage such as ILUC		To be determined case by case
1) CCS, per t of biogenic CO_2 removed and stored • **Net GHG emissions = (-A + B + C + E) * process-level allocation factor (54%) / (D – E)**			**-0.52 t CO_2e/t biogenic carbon removal (excluding potential leakage or avoidance)**
2) Exported electricity, per MWh • **Net GHG emissions = (-A + B + C + E) * process-level allocation factor (40%) / exported electricity**			**-0.89 t CO_2e/MWh (excluding potential leakage or avoidance)**
3) Exported heat, per GJ • **Net GHG emissions = (-A + B + C + E) * process-level allocation factor (6%) / exported heat**			**-0.14 t CO_2e/GJ heat (excluding potential leakage or avoidance)**
Leakage and avoidance • **For CCS = (G – F) / (D – E);** • **For exported electricity = (G – F) / exported electricity;** • **For exported heat = (G – F) / exported heat.**			**To be determined case by case**

Alternatively, the process-level allocation method can be applied to split the energy and emission burdens between carbon removal and bioenergy production based on the process-level energy and carbon flows as presented in Figure 8. In this example, all material/energy use and associated emissions are allocated among CO_2 removal and storage, exported electricity, and exported heat.

In this BECCS facility, 7.3 GJ of heat is produced from 1.25 wet t of biomass, which is then split into three routes. The main part (60% of heat) is used for electricity generation (720 kWh) among which 24% (170 kWh) is used for CCS and 60% (430 kWh) is exported. Among 7.3 GJ of heat from the boiler, 34% (2.5 GJ) is used to capture CO_2. Thus, the CCS unit consumes 48% (=34% + 60%*24%) of total heat produced, while exported electricity and exported heat are responsible for 36% (=60%*60%) and 5%, respectively. Note that 120 kWh electricity, which consumes 10% (=60%*120/720) of the total heat produced, is used for the facility operation, which should be allocated among the three products. One way to allocate the commonly shared electricity in the facility is based on the heat demands of the CCS, exported electricity, and exported heat, i.e., 48%, 36%, and 5%, respectively. This adds 4.8%, 3.6%, and 0.5% of the total heat production to the heat demand of the CCS, exported electricity, and exported heat, respectively. As a result, 52.8% (=48%+4.8%), 39.6% (=36%+3.6%), and 5.5% (=5%+0.5%) of the total heat production is consumed by the three products, respectively. On a relative basis, the total heat consumption among these three products is split by 53.9%, 40.4%, and 5.6%, respectively, which is applied to split the overall heat demand among the three products, respectively.

5. Summary and closing

Consistent and robust LCA is pivotal to evaluating the net GHG emissions and broader life cycle environmental impacts of BiCRS technologies. This document builds upon the ISO 14040/14044 standards specifically for the evaluation of BiCRS systems, including dedicated systems that focus on biomass carbon removal and storage and BECCS systems that provide bioenergy. The best practices provided in this document apply to BiCRS with durable carbon storage for at least 100 years in alignment with the Carbon Negative Earthshot.

Extensive efforts are often required to conduct a holistic LCA of a complicated system such as a BiCRS technology. LCA efforts could be well planned in recognition of the key issues involved in the LCA, as well as the level of uncertainty and potential impact on the robustness and accuracy of the results. Figure 9 summarizes high-level assessment of the levels of uncertainty and impact related to addressing specific LCA issues for BiCRS technologies.

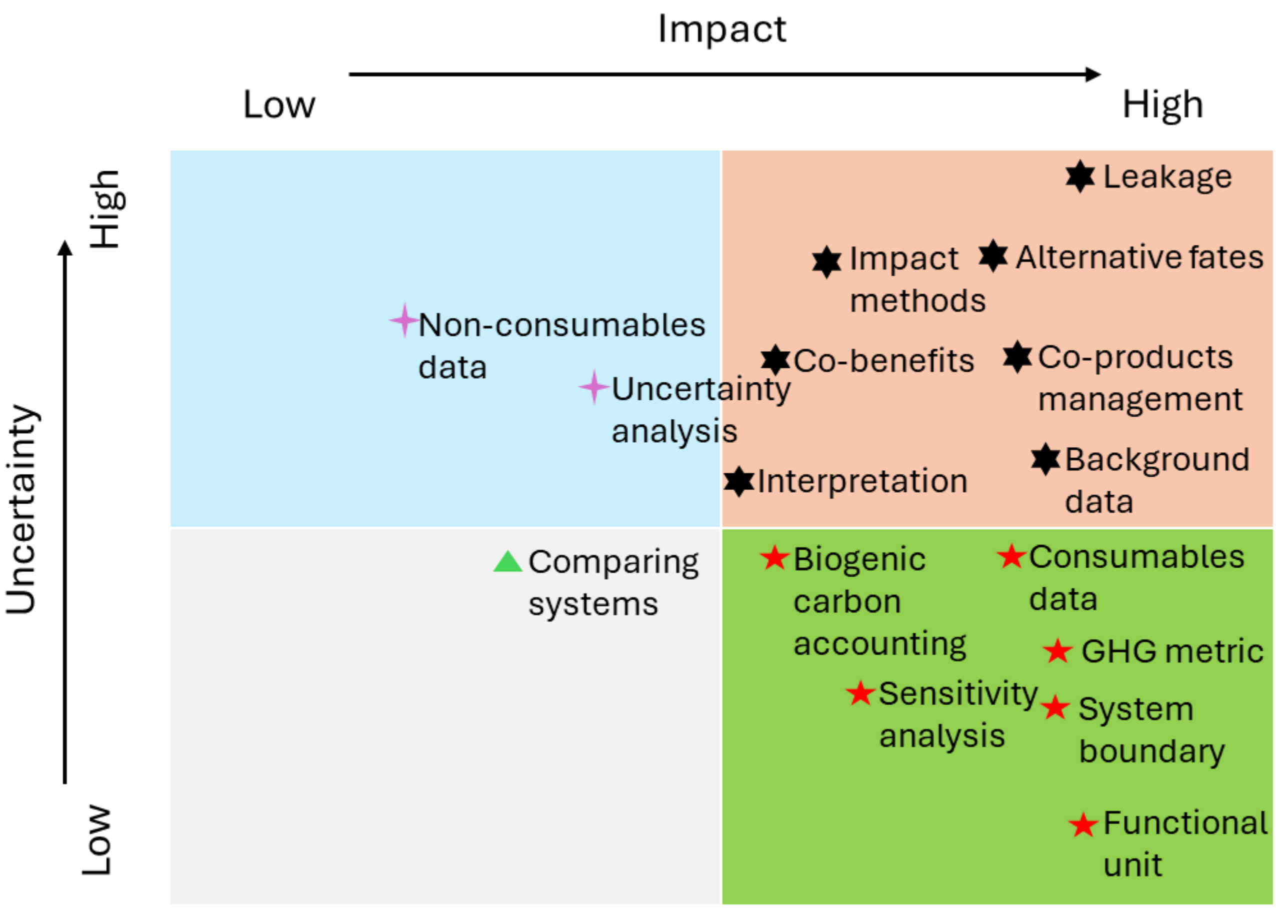


Figure 9. Levels of Uncertainty and Impact on LCA Results Related to Addressing Key LCA Issues for BiCRS Technologies.

It is considered relatively lower uncertainty to define a quantitative and meaningful system boundary, functional unit, and GHG metric following the best practices laid out in Sections 3.1.1, 3.1.2, and 3.1.4, despite the utmost impact on the LCA results. It may involve extra consideration of key purpose(s) of the BiCRS systems, especially for BECCS systems, which add some uncertainty to defining a comparable system. While it provides important insights by benchmarking the BiCRS system to a comparable system, it does not change the results of the BiCRS system.

For biogenic carbon accounting, the explicit approach laid out actionable steps that can quantify the impacts of biogenic carbon flows in the BiCRS system sufficiently, but it requires comprehensive tracking of the biogenic carbon flows across all the processes involved and thus present challenges and uncertainties. For consumables data, they are critical to determining the quantitative LCA results and often require major data collection, processing, and validation efforts to assemble. Nonetheless, these data could be clearly defined and curated using a well-characterized LCI data template focusing on primary operational data, which makes the effort generally manageable. On the other hand, data for non-consumables often require indirect, supply chain, and third-party information that the BiCRS operator may not track explicitly, such as the bill of materials of specific equipment or infrastructure development, and thus adds complexity, effort, and uncertainty to develop quality data. However, given that the non-consumables may be designed to operate for a long period of time, their impacts should be amortized over the period, which could lead to relatively small impacts. Background data such as electricity generation and transmission to the BiCRS facility may be curated using different datasets and methodologies, leading to variability and uncertainty among LCA databases and models. They could influence the LCA results significantly, making this issue an important one for the LCA community to continue to harmonize and build consensus.

Co-product management methods could be very influential on the LCA results, while the choice of specific methods could be somewhat subjective and could vary by the process design and objectives of the BiCRS systems. This, among other issues, could add challenges and uncertainties when it comes to interpretation of the LCA results for contexts of interest. Impact methods that address not only climate impacts but also a spectrum of other issues such as air quality and ecosystem services generally have poor spatial and/or temporal resolution and may simplify underlying physical, chemical, and biological processes that interact with the environment and human beings, introducing relatively large uncertainties. Consequential impacts such as ILUC and indirect effects are known to have great uncertainty given the complex and uncertain causality and feedback loops among biomass sourcing scenarios and potential market mediated responses that may involve multiple economic sectors at different temporal and spatial scales. Some of these may present co-benefits that may rely on configuring, calibrating, and customizing external, process-based modeling frameworks with data relevant to specific BiCRS systems. Other consequential impacts such as alternative fates may be complicated and vary widely for specific biomass sourcing strategies, could be challenging to identify, and uncertain to quantify the associated emissions and other impacts.

Given the uncertainties associated with these analytical issues, uncertainty analysis and sensitivity analysis are often deployed to identify causes for the uncertainties and quantitatively estimate the impact of major causes. With established quantitative methods and procedures, uncertainty analyses have become feasible when sufficient data needed could be collected. In the meantime, sensitivity analyses may provide insights without requiring extensive data, making it a useful technique to improve the LCA by identifying and focusing on important issues, while assisting meaningful interpretation of the LCA results.

As a quick guide on the best practices for overall LCA of BiCRS systems as well as for specific LCA issues discussed above, Table 6 includes a summary of all the best practices detailed in this document. The qualitative and quantitative portions of each of the Best Practices discussed in this document should be included in the LCA report, in addition to elements described in Section 5 of ISO 14044.

Table 6. Best Practices of Key LCA Issues Associated with Major LCA Stages of BiCRS Systems.

LCA Stage	LCA Issue	Best Practice(s)
Goal and scope definition	Goal	• Evaluate BiCRS technologies to estimate net GHG emissions and carbon intensities with holistic LCA.

LCA Stage	LCA Issue	Best Practice(s)
	Functional unit	• Analyze BiCRS using this functional unit: Mass of carbon from the biomass that ends up stored durably for at least 100 years, regardless of the forms of the stored carbon resulting from various biomass conditioning and/or conversion strategies, if any.
	System boundary	• Evaluate BiCRS with a cradle-to-grave boundary to fully account for the function of the system. • Depict the system boundary and encompassing processes graphically using a process flow diagram. • Separate accounting for indirect emissions such as induced land use change emissions and emissions from alternative fates, if applicable. • Separate accounting for embodied emissions associated with non-consumables. • Separate net CO_2 removal and storage from avoided emissions
	GHG metrics	• To address the climate impacts of BiCRS, report the net CO_2e emissions of a BiCRS technology.
	Defining comparison systems	• Ensure functional equivalence between systems, including the management and provision of relevant alternative fates and co-products for all systems under evaluation. • Document assumptions regarding the future landscape into which the BiCRS technology might be deployed at scale, including identifying technology improvement over time. • Use consistent assumptions and data quality requirements for background data for all systems to ensure equivalent comparability. • Represent the system boundaries for the different systems visually to communicate consistency when comparing two or more BiCRS or CDR systems.
Life cycle inventory analysis	Data Collection – Non-Consumables	• Compile bill of material/equipment data for the actual facility construction when available. • Utilize a modeling approach that provides the best data that is available to represent these activities corresponding to the stage of development. • Update representation of design and underlying LCI data as technology matures and nears deployment. • Test sensitivity of the assumed facility lifetime and any non-consumables that require replacement during the facility's operating life.
	Data Collection - Consumables	• Coordinate with process engineering modeling team and/or facility operators to compile operational energy and material balance data necessary for LCA, including physical quantities for biomass feedstock and process inputs and outputs (e.g., MJ energy, kg materials) in addition to the associated inventory of non-combustion emissions (e.g., kg non-combustion emissions). • Separately report and account for any captured fossil or other non-biomass-derived CO_2 (e.g., from on-site fossil fuel combustion) from the biomass carbon that is captured and stored for consistency with the functional unit. • When multiple potential sources/types are being evaluated as part of the design, develop separate LCA scenarios for each. • Clearly identify degree of uncertainty and variability, particularly for modeled rather than measured inputs.

LCA Stage	LCA Issue	Best Practice(s)
	Co-Product Management	• Follow the established co-product management hierarchy in ISO 14044. • If subdivision is not possible, use system expansion with a multiproduct functional unit. • Avoidance and removals should always be accounted for separately and transparently. • Maintain a record of the physical system depicting the impacts with and without management of co-products. • Test multiple co-product management approaches, including allocation. This can help determine how robust conclusions are across multiple approaches.
	Impact methods	• Use the EPA's TRACI version 2.1 method for LCIA to characterize broad impact categories. • Use the IPCC AR6 GWP characterization factors for translation of GHG emissions to Global Warming Potential impacts as a replacement for the factors in TRACI, and adopt future IPCC GWP characterization factors as they are released.
Interpretation	Overall LCA methodology and results	• Assess the completeness of the LCA. Ensure that the LCA covers all significant stages of the life cycle of a BiCRS system within the defined system boundary and verify that data for all life cycle stages is not missing or excluded. • Check data quality. Evaluate the quality and representativeness of the data used in the LCA. Consider factors like geographical, temporal, and technological relevance. • Conduct hotspot analysis. Identify which stages of the life cycle, processes, or materials contribute most significantly to the impacts. This helps identify opportunities for improvements. • Interpret causal relationships. Understand the causal relationships in the life cycle to explain why certain processes contribute more to specific impacts. • Quantify uncertainty: Include uncertainty analysis to understand the variability in the results. This could involve stochastic modeling techniques such as Monte Carlo simulations and sensitivity analysis by identifying and varying impactful input parameters and assumptions that reflect potential operating envelope to evaluate how they affect the LCA results. • Perform scenario analysis: Perform scenario analyses to evaluate how different assumptions or conditions impact the results, providing a more comprehensive view of potential outcomes. • Develop actionable insights: Interpret results with a focus on providing actionable insights. Suggest potential improvements or mitigation strategies based on the findings. • Create a feedback loop: Use the results to inform and refine the initial goal and scope of the study, creating a feedback loop for continuous improvement. • Plan for continuous improvement: Recognize that LCA is an iterative process. Regularly update the assessment with new data or methodologies, and review interpretations as new insights or data become available.

LCA Stage	LCA Issue	Best Practice(s)
	Sensitivity and uncertainty analysis	• Conduct hotspot analysis to identify key parameters and conduct sensitivity analysis of the key parameters considering reasonable ranges of variability and possible causal relationships with other parameters. • Given well-characterized data that reflect actual operational conditions that may vary within normal ranges including downtime, perform stochastic simulation-based uncertainty analysis to propagate uncertainty/variability associated with multiple key parameters within the system boundary of a BiCRS system. • Use scenario analysis and consider bounding scenarios to inform key decision points.
Unique issues	Impacts of alternative fates	• Discuss specific alternative fate(s) that may be avoided solely due to diversion of the biomass to the development and deployment of the BiCRS technology. If multiple alternative fates may be expected, discuss the likelihood of each and conduct scenario analysis for each. • Ensure that the alternative fate(s) is realistic and relevant to the context of the biomass production or sourcing of waste/residue carbon resources. It should be plausible and based on historical trends, business-as-usual biomass production/management plans, or market conditions for the specific source of biomass. • Seek stakeholder input: Involve stakeholders in the development of alternative fates to ensure that they are relevant and reflect the perspectives of those affected by biomass production. Stakeholders may include local communities, policymakers, industry representatives, and environmental groups. • Define an appropriate time horizon for the alternative fates assessment, considering both short-term and long-term impacts. The effects of biomass production/management may vary significantly over time. • Consider the spatial scale of the assessment. Alternative fates may need to be evaluated at local, regional, or global scales, depending on the scope of the biomass production/management that are influenced. • Conduct sensitivity analysis to evaluate the geographic location and local environmental conditions that may affect emissions, carbon sequestration, and other ecosystem impacts associated with alternative fates. • Quantify emission implications of the alternative fate(s) with the best available measurement, empirical, or modeling data. • Assess broad ecosystem impacts that may be relevant. For example, assess how the use of forest biomass affects forest ecosystems, including biodiversity, soil health, and water cycles. • Clearly document the data sources, assumptions, and methods used in the analysis of specific alternative fate(s) to ensure transparency and reproducibility.

LCA Stage	LCA Issue	Best Practice(s)
	Induced land use change impacts	• Clearly define the boundaries of the ILUC modeling, including geographic scope, time horizon, and the types of biomass being evaluated (e.g., energy crops and woody biomass). • Employ economic and land use models that can capture the dynamics of global agricultural markets, land availability, and crop productivity. Models like Global Trade Analysis Project (GTAP) (Purdue University, 2024) or Global Biosphere Management Model (GLOBIOM) are commonly used (IISA, 2024). • Validate models with historical data and compare them with other models to ensure robustness and reliability in predicting ILUC. • Develop multiple scenarios to capture the range of possible outcomes. Scenarios might include different assumptions about biomass demand, agricultural productivity, policy interventions, and technological developments. •Consider how existing and proposed policies and carbon pricing influence land use decisions and the extent of land conversion. • Assess how market dynamics, such as global commodity prices, influence the economics of land use change. The profitability of biomass production relative to other land uses is a key driver of ILUC. • Perform sensitivity analysis to understand how changes in key parameters (e.g., biomass yield, demand for biomass) affect the results, highlighting which factors have the most significant influence on ILUC. • Evaluate how ILUC affects carbon stocks, both aboveground (forests, grasslands) and belowground (soil carbon). Include direct emissions from land conversion and indirect effects such as changes in agricultural practices. • Be transparent about the assumptions and limitations of the models and data used. This transparency helps stakeholders understand the uncertainty and variability in the results.
	Co-benefits	• Include and discuss co-benefits such as soil improvement, waste reduction, or job creation at least qualitatively if relevant to the system, e.g., when agricultural residues, food waste, or forest residues are used as feedstocks. • Co-benefits are highly dependent on local conditions, such as soil type, climate, and social-economic conditions. Ensure that the LCA reflects regional specifics where the BiCRS system is implemented.
	Biogenic carbon accounting	• Apply an explicit carbon accounting approach to estimate all relevant carbon stock and emissions fluxes in the BiCRS system.

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Appendix

A1: Necessary conditions for BECCS systems

- BECCS systems must produce gross energy outputs across the system boundary using the energy source in the form of biogenic carbon.
- The primary purpose of the products should relate to energy production; energy production may be in the form of one or more fuels/energy carriers, including electricity, heat, hydrogen, liquid fuels, pellets, ammonia, or others. For instance, if ammonia is used primarily as a fertilizer feedstock, the system would likely not be categorized as BECCS.
- The system should be designed to capture and sequester most of the carbon that is not part of the fuel/energy products for long periods of time (~100 years). Regarding carbon sequestration, two separate views have been noted in the literature. Some have categorized only geologic CO_2 storage to be consistent with BECCS (Fajardy, 2022) while others include systems producing any forms of carbon sequestration (e.g., biochar) that co-produce distinct energy (Li et al., 2021). Consensus reports such as those by the U.S. National Academy of Sciences (National Academies of Sciences, Engineering, and Medicine, 2019) and the IPCC (Clarke et al., 2022) state that such systems may also correspond to BECCS if they are producing energy outputs.

A2: Additional Information on Biogenic Carbon Accounting

Biogenic carbon refers to the carbon originating from biomass via photosynthesis. Biogenic carbon may need to be accounted for separately from fossil carbon, given the vast difference in the timeframe required to complete the life cycle of biogenic carbon and fossil carbon. The life cycle of biogenic carbon could take from within a year for annual crops to years for short-rotation woody biomass and to decades for certain softwood and some hardwood species to complete; the life cycle of fossil carbon may take millions of years. When fossil carbon is converted into CO_2 primarily via combustion, such emissions are universally considered additional, positive emissions in LCA. However, biogenic carbon and related biogenic CO_2 may be handled differently considering its much shorter life cycle.

In biofuel LCAs, biogenic carbon from annual biomass resources is generally handled with an approach that assumes that “the CO_2 emissions from the combustion/oxidation/decay of annual biomass are balanced by carbon uptake prior to harvest, within the uncertainties of the estimates, so the net emission is zero.” (IPCC 2019). This approach is recommended in ISO 21930:2017 (ISO 2017) and is reflected in several policy guidelines, including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO 2023) and Low Carbon Fuel Standard (LCFS) methodologies (CARB 2024). More precisely, in this approach biogenic carbon is considered a carbon sink when it enters a system such as a BiCRS system, with a factor of -1 kg CO_2e/kg biogenic carbon. The biogenic carbon is considered carbon emissions when it exits the system, with a factor of +1 kg CO_2e/kg biogenic carbon. Any biogenic carbon that ends up durably stored in the system is considered a carbon sink; thus, a factor of -1 kg CO_2e/kg biogenic carbon should be applied. This is known as the (-1/1) approach. Note that the ISO language does not indicate whether biogenic CO_2 emissions should be reported based on the declared product mass and composition.

This approach has been called “carbon neutrality” due to the “neutral” (i.e., net zero) assumed result of the biogenic carbon. However, the term “carbon neutrality” has also been used to refer to the biogenic carbon balance for long-rotation forestry biomass for which the biogenic carbon accounting is much more variable based on the age, location, and species of biomass as well as the circumstances around the growth of the feedstock and its collection. “Carbon neutrality” has also been used to apply to the GHG profile for bioenergy production, implying that bioenergy production is net zero inclusive of process emissions associated with the collection, transporting, and processing of the biomass as well as emissions from activities within the plant gate. Given the ambiguity of the term “carbon neutrality" and the range of uses of it, we will avoid using it in this document and instead to "net zero biogenic carbon" where appropriate.

In practice, the net zero biogenic carbon approach that has been used in bioenergy LCA simplifies the biogenic carbon accounting and required data collection, verification, and validation processes by treating any biogenic CO_2 emissions exiting the system as carbon neutral and thus *not* to account for such emissions (i.e., a 0/0 approach). The simplified (0/0) approach presents several drawbacks, which make it unviable for BiCRS LCA:

(1) Certain fates of the biogenic carbon may be ignored, such as biogenic carbon from the biomass that ends up in co-products and/or waste streams. This presents a risk of potential neglect of storage of the biogenic carbon from co-products and/or waste stream as they go through their own life cycles.

(2) The biomass production system from which a BiCRS technology draws biogenic carbon may produce additional biogenic carbon (e.g., corn stover) that contributes to other carbon pool, such as soil organic carbon (SOC), which may present as co-benefits that should be considered separately. Conversely, if the BiCRS technology sources biomass feedstocks that otherwise would have contributed to the soil organic carbon pool, there may be a SOC penalty, which should be considered.

(3) The (0/0) approach assumes *a priori* that the amount of carbon emitted from the combustion of the biomass is equal to the carbon sequestered in the growth of the biomass. This ignores potential alternative fates for the biomass that could violate this math. For example, considering the potential use of woody biomass from natural forests, for any living biomass harvested and collected that biomass would have continued to grow and accumulate carbon if it wasn't harvested. Considering woody biomass from forest plantations, forest owners have flexibility in advancing or delaying harvests depending on market conditions that affect the carbon sequestered in the forest stand, and markets for BiCRS could affect that decision making. Considering residual forest biomass (e.g., slash from a harvest or dead biomass on the forest floor otherwise), there may be impacts positive impacts on soil carbon from the material naturally decaying on the forest floor that are lost when the biomass is removed (building on the second point above). These scenarios outline the need to consider the alternative fates or "counterfactuals" associated with the use of biomass feedstock for BiCRS applications that affect the LCA carbon score of the biomass.

A second practice, which we're recommending as the best practice for BiCRS LCA, is to explicitly track the mass balance of biogenic carbon entering and exiting a system, inclusive of carbon impacts from alternative fates. If this exercise were hypothetically to result in a (-1/+1) result for the resulting net biogenic carbon emissions or sink, then it would functionally be the same result as the (0/0) approach (i.e., net zero). This is illustrated in Figure A1 with a notional example.

This hypothetical system involves pyrolysis of biomass to produce fuel oil and biochar. Half of the carbon in the biomass is fractionated into the fuel oil and the other half in the biochar. The fuel oil combustion emits all the carbon into the atmosphere. In the case of the biochar, 80% of it remains stored while the rest is re-emitted into the atmosphere.

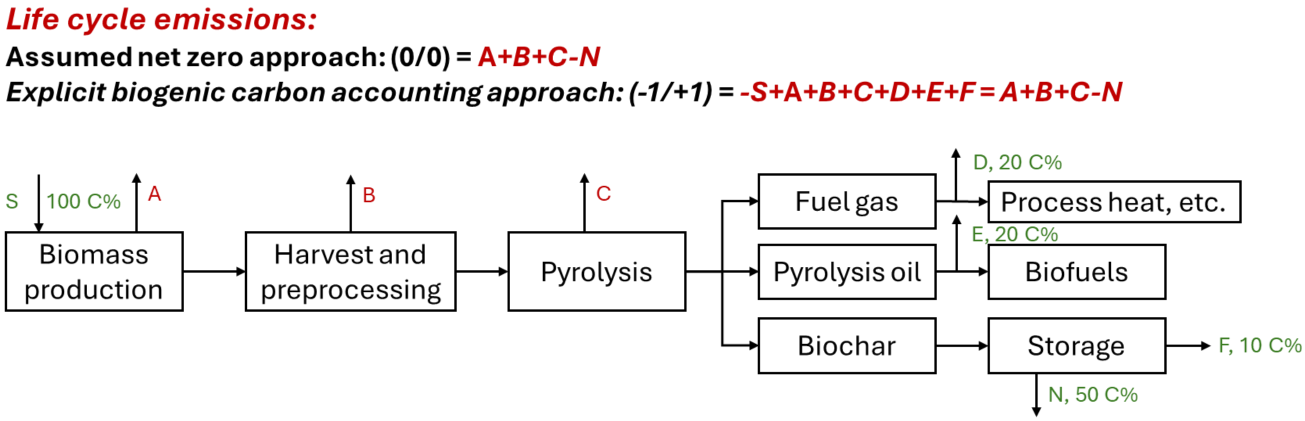

Figure A1. Illustration of the (0/0) and (-1/+1) approaches for a hypothetical biomass pyrolysis system. Here, A + B + C are the total process GHG emissions across the supply chain excluding biogenic CO2 emissions from the processes, as depicted by $E_{P,F}$ in Equation (1); D + E are the biogenic CO2 emissions from processes, as depicted by E_{P,Bio_C} in Equation (1); F are the physical leakage of biomass carbon after storage, as depicted by $-Bio_{C_L}$ in Equation (1); N is the biogenic carbon removal and storage in the biochar, as depicted by Bio_{C_S} in Equation (1).

With the (0/0), or assumed net zero, approach the biogenic CO_2 emissions from fuel gas combustion for process heat generation, etc. (D), the biogenic CO_2 emissions from making and use of biofuels from pyrolysis oil (E), if any, and any leakage of biogenic carbon in the biochar during storage (F), are considered carbon neutral emissions and are not accounted for, whereas biogenic carbon storage in the biochar (N) is accounted for as carbon storage. Fossil emissions during the biomass-to-biochar supply chain, which encompass emissions from biomass production (A), biomass harvest and preprocessing (B), and pyrolysis (C) are accounted for in this hypothetical system. Accordingly, the net life cycle emissions with this approach are (A + B + C – N).

With the (-1/1) or explicit biogenic carbon accounting, approach the biogenic carbon uptake during biomass production is accounted for as a net carbon drawdown (S). Unlike the assumed net zero approach, emissions from processes D, E, and F are accounted for, which offset part of the initial carbon drawdown (S). Biogenic carbon that remains stored in the biochar is assigned a value of 0 to avoid double counting. As such, the net life cycle emissions are (A + B + C – S + D + E + F). Since the carbon storage in the biochar (N) equals the remainder of the initial carbon drawdown (S) offset by biogenic emissions during the processes (i.e., D + E + F), the net life cycle emissions of this system equals (A + B + C – N). As such, both approaches give identical results.

Note that this illustrative example focuses on direct emissions from the carbon drawdown during biomass production to the biochar application as a BiCRS approach. It does not consider more complicated baseline conditions that may include impacts from alternative fates in which additional emissions or avoided emissions/foregone carbon sequestration may manifest. Additional adjustments to include such emission impacts, if applicable, are required. The best practice is to report such adjustments separately.

Explicit accounting of biogenic carbon requires consideration of several factors including the type of baseline, the type of feedstock, the timeframe of the assessment, and spatial scale that serve as the technical basis for evaluating biogenic carbon impacts associated with a system as described in Section 3.5 of this document.