Accounting Methods Dictate Carbon Removal Credit Integrity and Outcomes

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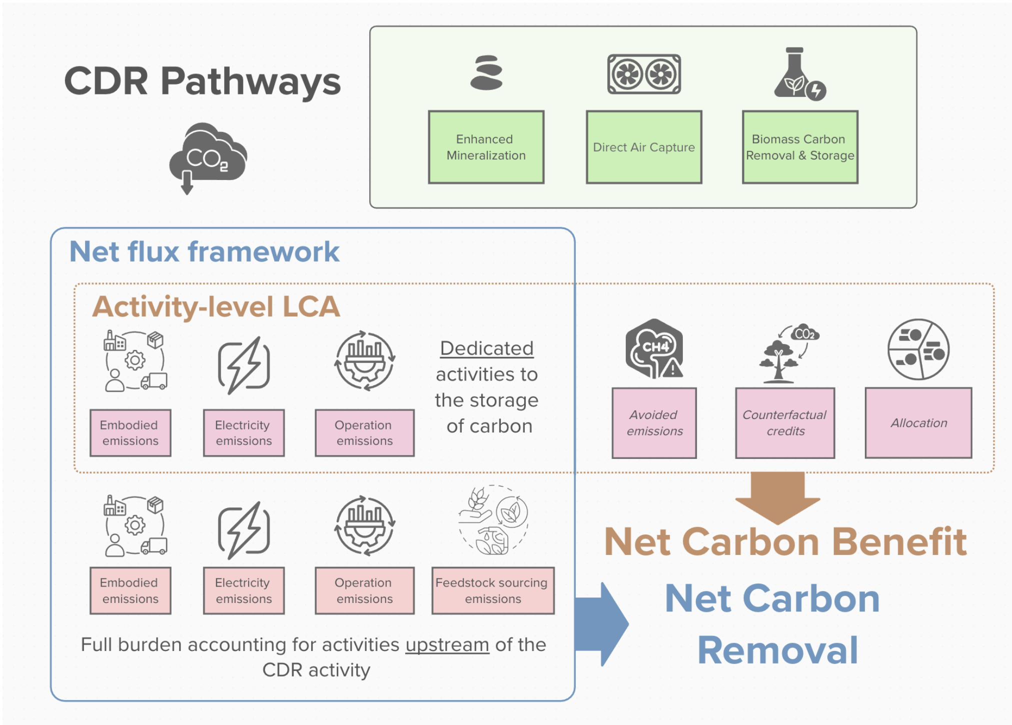
Abstract

Carbon dioxide removal (CDR) is distinct from emissions offsets. CDR commands a price premium relative to offsets, yet some accounting methods blur the line between them. This paper compares the project-level net CDR and economic outcomes of two carbon accounting methods — life-cycle assessment (LCA) and the net flux framework (NFF)—using nine examples spanning direct air capture and storage (DACS), biomass carbon removal and storage, and land-based mineralization. The NFF's expansive system boundaries typically translate to less CDR calculated for systems that also produce non-CDR outputs (e.g., fuel or electricity). For example, the NFF can reduce CDR-related revenue from a typical crop residue gasification project by over half relative to LCA, and would disqualify corn-to-ethanol CCS projects from selling CDR. Conversely, LCA of the narrowly-defined carbon storage portion of a project incentivizes retrofits to existing industrial facilities, which complicates the distinction between emissions reductions and CDR, placing more scalable but costly standalone CDR technologies at a competitive disadvantage.

Graphical Abstract



Key words: carbon dioxide removal, direct air capture and storage, biomass carbon removal and storage, mineralization, net removal, carbon accounting, life cycle assessment, biochar, geologic CO_2 sequestration

Main

Since the late 1980's, entities have sought opportunities to set and meet environmental goals that require them to reduce emissions beyond what is possible through their own direct actions. Carbon dioxide removal (CDR) emerged in the last decade as a high-quality, verifiable means of reaching long-term environmental goals by compensating for legacy and hard-to-abate emissions on a global scale.[1,2] These goals have raised unique challenges and questions about how well standard accounting methods such as life cycle assessment (LCA) align with CDR's stated purpose.[2,3] Accounting methods for CDR have substantial economic and environmental implications; there have been over $3 billion in total CDR sales to-date and a 2025 market survey showed that purchases of "durable" CDR are expected to grow by 24-fold by 2050.[4,5] There is broad recognition that consensus in carbon accounting methods would provide certainty, stability, and opportunities for growth in the industry, but viewpoints differ on what that consensus-based approach should be.[4–8]

Markets that sell CDR credits require the answer to a basic question: how much salable CDR does a given project accomplish? Motivated by the desire to protect and further improve confidence in CDR, there has been a proliferation of protocols and measurement/monitoring, reporting, and verification (MRV) entities.[12] These bodies publish accounting frameworks and protocols, drawing heavily from standard life-cycle assessment (LCA) approaches. The LCA approach, usually designed to estimate net CDR for a narrowly-defined CDR activity (e.g., a biogenic CO_2 capture retrofit) relative to the status quo, is supplemented with a patchwork of guardrails and other adjustments, often made on a project-by-project basis, to avoid outcomes deemed undesirable by individual MRV entities.[13–33] However, each case-specific adjustment adds complexity, creates challenges for future translation to policy applications, and leaves open the possibility that downward price pressure will incentivize maximally permissive interpretations. Further complicating the landscape, the goals for a given set of standards and protocols are rarely articulated. Appendix 1 of the Supplementary Information provides a partial review of CDR protocols, spanning a range of relevant technology classes of engineered CDR.[14–33]

An alternative to the LCA approach, the Net Flux Framework (NFF), dispenses with many of the standard LCA practices, such as co-product allocation and counterfactual avoidance credits, in favor of methods meant to quantify the net carbon removed from the atmosphere by a project and all the systems on which it relies.[2] In essence, the NFF answers the question: if a given project is deployed, inclusive of all the products and systems it relies on, how much CO_2 would be removed, on net, from the atmosphere? Since its introduction, the NFF has been debated and adopted by some in the CDR community.[13,34–37] This study directly analyzes and compares the results of an

LCA-based framework with the NFF for a series of direct air capture and storage (DACS), biomass carbon removal and storage (BiCRS), and land-based mineralization examples to demonstrate how methodological choices translate to accounting outcomes.

For the purposes of this paper, we consider three distinct metrics: (1) "gross storage", (2) "net carbon benefit" as quantified by activity-level life-cycle assessment (LCA), and (3) "net removal" quantified using the NFF. "Gross storage" represents total carbon placed in stable storage. "Net carbon benefit" represents the narrowly-defined life-cycle carbon balance for the CDR *activity* (hence our term "activity level LCA," e.g., a biogenic carbon capture and storage unit) with conventional, consequential LCA methods for including upstream emissions and crediting co-products. "Net removal", in contrast, uses the most expansive system boundaries (e.g., the full extent of an industrial facility that incorporates CDR, as well as its upstream impacts) and excludes the emissions reduction value of co-benefits. Previous studies have explored variations of these metrics but have not done a systematic comparison. For example, the *Roads to Removal* report's estimates of BiCRS potential leveraged agricultural residues without assigning the crop's full impacts to that material, as would be the case if using the NFF.[38] A U.S. DOE report outlined best practices for conducting LCA of BiCRS, but did not explicitly address what role LCA should play, if any, in calculating the value (tonnes of CO_2 removed) for CDR credits generated by an individual project.[39] Multiple papers and reviews from recent literature describe variability and weaknesses in LCA-based removal accounting metrics but do not provide a quantitative comparison of such metrics across engineered CDR technology classes.[8,13,40–42]

This paper quantifies gross storage, net carbon benefit, and net removal for nine illustrative examples: (1) solvent-based DACS, (2) sorbent-based DACS, (3) corn-to-ethanol biorefinery with carbon capture and storage (CCS), (4) pulp mill with CCS, (5) Bioenergy with carbon capture and storage (BECCS) using sawmill residues, (6) BECCS using corn stover, (7) switchgrass pyrolysis for biochar production, (8) land-based mineralization using excavated rock in greenhouses, and (9) land-based mineralization using excavated rock tilled into in-situ managed land. We assess the results to illustrate the differences between accounting methods and explore the implications of using each metric for CDR purchasing standards. By investigating a set of worked examples, we systematically assess the practical challenges and advantages of applying all three accounting methods, identify issues that require further refinement of the methods, and illustrate how each accounting approach impacts the final project-level results.

Results

This paper focuses on engineered, closed-system CDR technologies which can be divided into three technology classes: DACS, BiCRS, and land-based mineralization. These classes are the most prevalent types of engineered CDR in the current voluntary carbon market.[43] Figure 1 depicts flow diagrams for each scenario and the system boundaries for activity-level LCA and the NFF. Gross storage system boundaries are not shown because these encompass only the carbon physically stored.

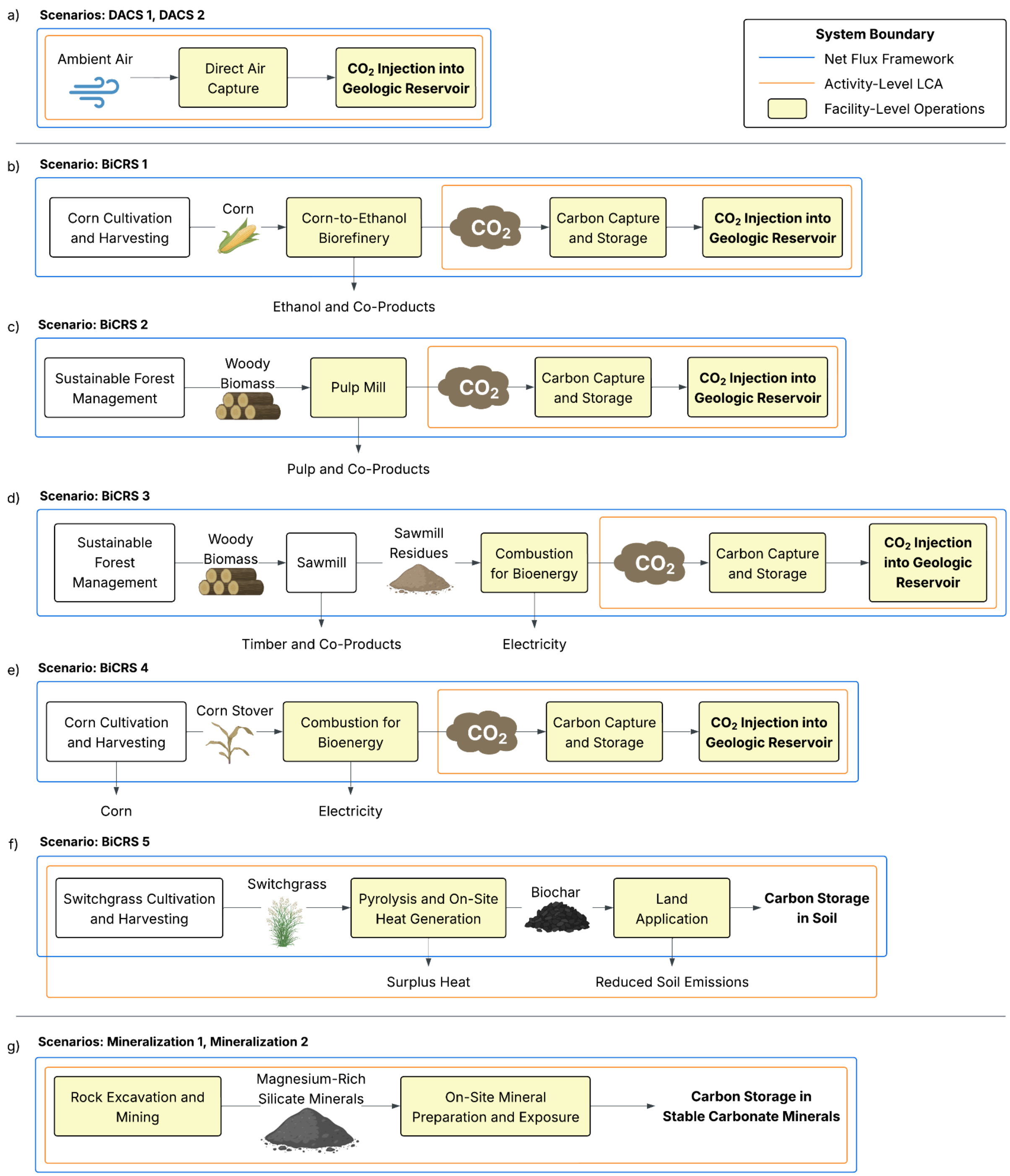


Figure 1. Scenario system boundaries and simplified flow diagrams.

Part (a) shows the system boundaries for both DACS scenarios: the only difference between scenarios is the direct air capture technology itself (solvent- vs. sorbent-based). Parts (b)-(f) depict each individual BiCRS scenario. Part (g) shows the system boundaries for both land-based mineralization scenarios: the differences between Mineralization 1 and Mineralization 2 is the method for mineral exposure to air (fans in greenhouses vs. in-situ tilling, respectively) and the primary type of equipment (electric vs. diesel-powered, respectively).

Activity-level LCA boundaries differ most from the NFF in multi-functional systems, such as an ethanol facility or a pulp mill that incorporate CCS (Figure 1b and 1c, respectively). In those cases, the LCA excludes most facility operations, only accounting for emissions directly related to the capture and sequestration of CO_2. The same holds true for sawmills and power generation facilities that incorporate CCS (Figure 1d and 1e). In other words, the analysis treats the primary operation (e.g., ethanol, paper pulp, or power production) as a given, assuming it would exist with or without the inclusion of CCS. For purpose-built CDR facilities, the system boundaries for activity-level LCA and the NFF are identical in many cases (Figure 1a and 1g). The primary difference is the treatment of co-products and other co-benefits (Figure 1f), which are relevant to multi-functional facilities. LCA methods dictate that co-products and other co-benefits be accounted for using system expansion (credits for the products/services displaced in the market by co-products/co-benefits) in calculating the net carbon benefit, whereas the NFF does not incorporate such credits. The Methods section and Appendix 2 of the Supplementary Information contain detailed modeling assumptions and process data.

Net removal and net carbon benefit

The 100-year net removal (as calculated by the NFF) and net carbon benefit (as calculated by activity-level LCA) resulting from 1 year of operation for 9 example scenarios are shown in Figure 2. Results are presented as a CDR efficiency, defined as the amount of net CDR credited as a fraction of total physical carbon stored, using each of the two frameworks (Figure 2). Detailed, tabulated results for each example are included in the Supplementary Information (Section 5 in Appendix 2). These results account for major contributors to emissions and benefits for each project type (e.g. direct emissions, emissions associated with raw materials or energy consumption) (see Methods for additional details). However, project-level accounting of real-world operations for market applications should be more comprehensive and rely on case-specific values that can be supported through measurement, monitoring, reporting, and verification (MMRV).

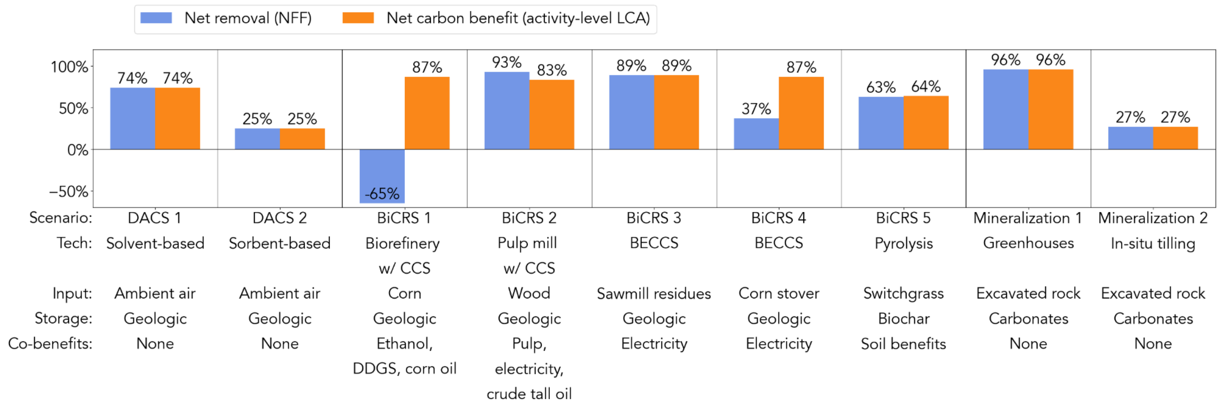


Figure 2. Carbon removal efficiency by scenario.
Efficiencies are defined by 100-year net removal or net carbon benefit as a percentage of gross storage. For example, a 50% CDR efficiency means that a facility using CCS must inject 1 tonne of CO_2 into storage for every 0.5 tonne of CO_{2e} (CO_2 equivalents) removal they can sell on the voluntary market.

Figure 2 shows that the NFF and activity-level LCA produce identical results for purpose-built, single-function CDR systems like the DACS and mineralization scenarios. DACS can achieve 25% (sorbent-based) to 74% (solvent-based) CDR efficiency using a US-average electricity grid mix. The higher efficiency achieved by solvent-based DACS is due to lower electricity consumption per-tonne of storage; however, local grid mixes and access to renewable energy can dramatically increase the efficiency for sorbent-based DACS.[44] Both examples of rock excavation for land-based mineralization achieve positive net removal. The first of these scenarios (Mineralization 1) achieves 96% efficiency by using electric equipment and by facilitating mineral-to-air exposure with fans in greenhouses. The second scenario (Mineralization 2), only achieves 24% efficiency because the exposure method is less effective (spreading minerals on land and occasional tilling) and most of the equipment is diesel-powered. While the first of these scenarios is more efficient with regards to carbon removal, the second method is easier to implement (i.e. requires less investment in new infrastructure) for existing mining operations that aim to reduce their carbon intensity by making use of mine tailings.

Net removal (NFF) and net carbon benefit (activity-level LCA) generally diverge for multi-functional systems and those relying on waste feedstocks because of differences in accounting for the upstream impacts of waste materials (BiCRS scenarios 1-4) and non-CDR co-benefits (BiCRS scenario 5). In the first four BiCRS scenarios, the CDR "activity" is the CCS unit(s). In these cases, the CCS units consume waste biogenic CO_2 from the primary facility (e.g., biorefinery, pulp mill) that otherwise would have been emitted to the atmosphere. CO_2 waste is treated as burden-free in LCA, meaning it carries none of the impact from the operation that produced it. However, the NFF uses expansive system boundaries and includes all upstream emissions associated with the production of the CO_2 waste stream (i.e., primary facility emissions and upstream feedstock production emissions). In many cases (BiCRS scenario 1, 4, and 5), the NFF produced lower calculated removal than activity-level LCA because of these expansive system boundaries. These nuances are better visualized in Figure 3 which shows the breakdown of CO_2e fluxes contributing to the final net carbon benefit (activity-level LCA) and net removal (NFF) metrics for the BiCRS examples. These results show the total penalty on gross storage as determined by either the NFF or LCA.

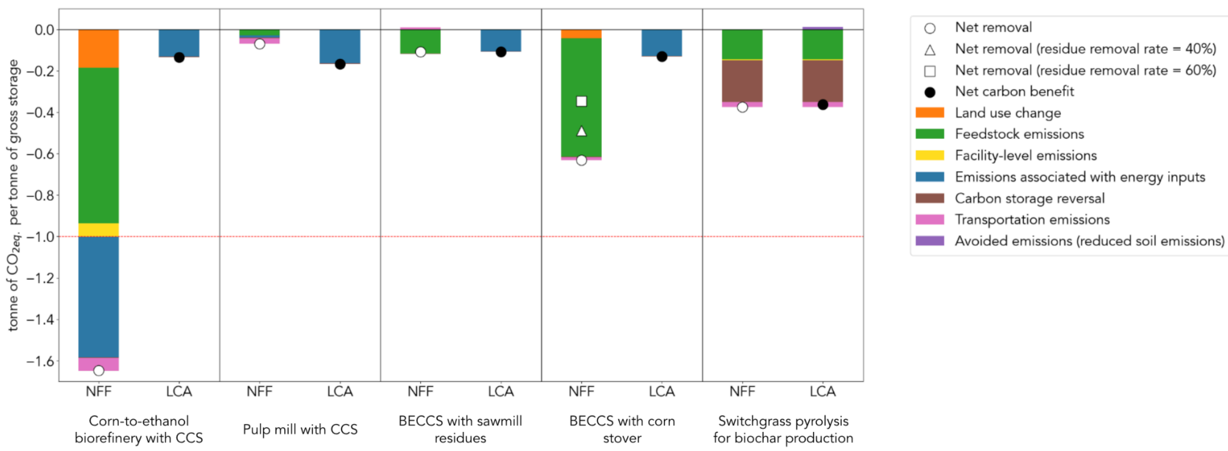


Figure 3. Deductions from and contributions to gross storage for net removal and net carbon impact for BiCRS examples.

Values represent the net emissions penalty applied to gross carbon storage to calculate net removal/carbon benefit. In a purchasing context, a net-zero value would indicate that 100% of gross storage can be sold as removals, a net value of -1 would indicate that 0% of gross storage can be sold as a removal, and a net value of less than -1 would indicate that the system is net-emitting. The horizontal red line distinguishes between net-removing and net-emitting systems. Net removal refers to Net Flux Framework (NFF) accounting results. Net carbon benefit refers to activity-level life-cycle assessment (LCA) results. Base corn stover results use a 30% residue removal rate.

The pulp mill with CCS example is unique in that the NFF produces higher calculated removal than activity-level LCA. Like the bioenergy facilities in the BECCS scenarios, the pulp mill facility produces electricity exceeding its own internal needs, and thus is net energy-exporting. Addition of the CDR activity (i.e. CCS), which consumes energy, reduces the facility's net energy exports. The NFF is agnostic to this fact (Figure 3). It does not assign credit for co-products nor does it calculate changes relative to a counterfactual (e.g., the facility operations pre-retrofit). When applying activity-level LCA, however, CCS is penalized based on its electricity consumption and the US-average grid carbon intensity (Figure 3). For the pulp mill scenario, the removal efficiency as calculated using activity-level LCA is 10% *lower* than the calculated removal efficiency using the NFF if the US-average grid emissions penalty is applied (Figure 2). For the same reasons, the removal efficiency as calculated by either the NFF or activity-level LCA is nearly equivalent for the BECCS scenario using sawmill residues.

Using activity-level LCA, CCS appears to be a reliable form of carbon removal, achieving CDR efficiencies of 83-87% when penalizing CCS electricity consumption with the US-average grid carbon intensity (Figure 2). This result will prove true even if, for example, the entire facility is a net-emitter of fossil CO_2, which is typically the case at corn ethanol facilities that capture biogenic CO_2.[45] However, in the NFF, not all CCS activities result in a net flux of CO_2 out of the atmosphere into durable storage; this is only true if the storage achieved by the CCS unit outweighs the CO_2e footprint of all upstream activities. This is not the case for the corn-to-ethanol biorefinery with CCS example, which produces the only negative result for net removal across all scenarios in Figure 2. While the CCS activity does lower the CO_2e footprint of the ethanol, the system does not result in a net flux of CO_2 out of the atmosphere. This is due, in large part, to emissions from corn cultivation and land use change (using values aligned with the Argonne National Lab GREET model)[46,47] (Figure 3). The NFF results in an additional 151% penalty on gross storage compared to activity-level LCA (approximately 13%), for a total final penalty of 165%. This is not an unexpected result because corn ethanol production is not designed for CDR but rather for biofuel production, which can be emissions-intensive.[48,49]

Corn cultivation is also a major penalty in the BECCS scenario using corn stover (Figure 3). According to the NFF, corn stover, like corn grain, takes on the full burden of corn cultivation. Above-ground corn stover biomass is produced alongside corn grain at a 1:1 ratio, implying that the carbon intensity of corn stover would be the same, on a mass basis, as corn grain. However, only a fraction of corn stover can be sustainably harvested and guidance for the fraction of stover that can be harvested varies depending on field-level tillage practices, slope, and crop rotation.[50] We conservatively assume 30% of corn stover is harvested without negative impacts on soil carbon and erosion.[50] This result is sensitive to the harvestable fraction of corn stover, so we provide additional analyses assuming a 40% and 60% harvestable fraction (denoted by the triangle and square icons in Figure 3, respectively). Despite the higher feedstock penalty for corn stover than corn grain on a mass basis, the corn stover BECCS scenario, in contrast to the corn ethanol case, still achieves a positive net removal using the NFF.

If there are coproducts generated within expansive system boundaries, the NFF favors systems that consume these coproducts internally and reduce input requirements over systems that sell coproducts for use outside of the system boundary. The last BiCRS example (switchgrass pyrolysis, shown in Figure 2 and Figure 3) is an example of a dedicated system, optimized for biochar production. All non-biochar pyrolysis products are combusted for on-site heat generation, thereby reducing the external energy consumption of the facility to near zero. The full impact of switchgrass cultivation is included in both activity-level LCA and the NFF because the system is purpose-built (i.e. switchgrass is not a waste product from another economic system). In this case, penalties on gross storage associated with net removal and net carbon benefit results differ by just 1% because of the inclusion of avoided emissions (e.g. reduced N_2O soil emissions from biochar application) in the LCA.

Role of carbon removal in facility-level economics

The differences in carbon accounting approaches have meaningful financial implications for both dedicated CDR facilities and existing industrial facilities seeking to sell CDR credits for retrofits. Table 1 provides a simplified revenue analysis, which only considers primary product revenue and additional revenue from CDR sales, for the CCS scenarios (BiCRS 1-4). In the case of corn ethanol facilities with CCS, selecting an NFF approach means these facilities are unlikely to sell CDR, whereas an activity-level LCA approach could mean additional CDR revenues equivalent to \$0.51 per gallon of ethanol, assuming a tonne of CO_2 removal is priced at the 2025 average BECCS-specific breakeven value of \$232.[51] This corresponds to a 30% increase in revenue if a gallon of ethanol is sold by the facility for \$1.70.[52] For pulp mills, the potential increase in revenue is estimated to be far smaller, resulting in a <1% increase in revenue relative to a no-CCS case, regardless of accounting framework. In contrast, the two BECCS cases shown in Table 1 indicate dramatic increases in revenue, suggesting that these facilities' economics would primarily depend on CDR revenue, with electricity sales making up a smaller share.

Table 1. Simplified revenue analysis for BiCRS scenarios with CCS.

Scenario	**Corn ethanol biorefinery w/ CCS**	**Pulp mill w/ CCS**	**BECCS w/ sawmill residues**	**BECCS w/ corn stover**
Primary product	Ethanol	Pulp	Electricity	Electricity
Product price	\$1.70 / gal [52]	\$1705 / tonne [53]	\$94.95 / MWh [54]	\$94.95 / MWh [54]
CDR price	\$232 / tonne [51]			
CDR revenue per unit fuel/electricity output				
NFF	\$0 / gal	\$12.89 / tonne	\$998 / MWh	\$339 / MWh
LCA	\$0.51 / gal	\$11.53 / tonne	\$998 / MWh	\$798 / MWh
Gross	\$0.59 / gal	\$ 13.83 / tonne	\$1118 / MWh	\$917 / MWh

% increase in total revenue from CDR				
NFF	0%	0.76%	1051%	357%
LCA	30%	0.68%	1051%	840%
Gross	35%	0.81%	1178%	966%

An important caveat is that these facilities can receive policy incentives for their fuel/electricity products that will alter revenue streams. For example, corn ethanol facilities qualify for a range of renewable fuel credits/incentives and BECCS facilities may qualify for region/state-specific programs, such as California's BioMAT program, which can increase the electricity revenue upwards of $120/MWh.[55] However, the magnitude of these incentives is not sufficient to alter the fundamental takeaways from Table 1.

Discussion

The choice of carbon removal and emissions accounting approach is subjective, complex, and has real implications for the profitability and long-term viability of different CDR technologies. The approaches adopted by policy-makers and private CDR market participants can shape the technology profile and growth rate of the global CDR market. As illustrated by the results in Table 1, an LCA approach to valuing CDR is likely to incentivize further expansion of CCS retrofits to existing industrial facilities. In some cases, these facilities already receive policy support designed to maintain or grow their industry, as is the case for biofuels.[56] Thus, these facilities may further solidify their competitive advantage over new, dedicated CDR facilities by stacking policy incentives, designed to reward producers of fuels, electricity, and other industrial products, with the opportunity to sell CDR. For example, tax credits are not generally considered to be a transferral of environmental attributes,[57,58] thus enabling claimants to collect credits for the same carbon removal they are also able to sell in private CDR markets. Inflation Reduction Act tax credits reward CCS through such credits as 45Q, 45V, 45Z, 45Y, and 48E.[59] In short, the potential to stack CDR sales revenue with tax credits, and other policy incentives that do not constitute a transfer of environmental attributes, advantages the same types of CDR technologies that will typically benefit most from the use of activity-level LCA accounting. If these facilities crowd out dedicated CDR, such as DACS, the result could be a delay in scaling up CDR technologies that are critical for reaching long-term stabilization goals.[3]

The NFF approach, in contrast to activity-level LCA, tends to favor standalone CDR facilities because of its expansive system boundaries and exclusion of co-product credits. In short, it draws a more clearly defined and restrictive line between emissions reductions/offsets and CDR. A valid critique of this approach is that it may exclude some of the most cost-effective options for emissions reductions. Retrofitting a corn ethanol facility would, in the case of the NFF, no longer be considered CDR. However, such an operation would still be free to sell emissions offsets and/or claim other incentives designed to reward emissions reductions. The NFF would still support retrofits and CCS activities that do result in a project-wide net flux of CO_2 from the atmosphere (e.g., the pulp mill and BECCS examples) and provide increased incentives for the development of dedicated CDR like DACS, which currently requires CDR prices nearly 3 times higher than typical BECCS projects.[51]

In developing consensus around carbon accounting approaches for CDR, there are valuable lessons to be learned from quantitative examples. These can be revealing, both in terms of the impacts on calculated carbon removal as well as the impacts on facility-level economic incentives. Our analysis underscores the need to align accounting methods with specific investment goals. Activity-level LCA can capture changes in net emissions, while the NFF focuses solely on atmospheric CO_2 removal. Although there is more work to be done, the fact that the NFF and activity-level LCA often produce similar results—diverging primarily in debated cases like corn ethanol and agricultural residues— suggests that the NFF can be a viable starting point in real-world MMRV standards. The NFF's conceptually simple approach to assessing net removal (did the full scope of this project result in net CO_2e removal from the atmosphere?) offers a level of confidence that cannot be achieved by adhering to LCA standards alone. Grounding MMRV standards in a simple, conceptual framework can help ensure a high-integrity market for scalable CDR solutions.

Methods

Goal and scope

The goal of this paper is to provide illustrative, quantitative CDR examples, identify differences between CDR metrics defined by NFF and by activity-level LCA, and the degree to which accounting methods lead us toward the broader goals of carbon removal. We consider 9 examples of CDR activities spanning 3 classes of CDR technologies (DACS, BiCRS, and land-based mineralization). Examples were selected based on industry relevance and data availability. For all analyses, we consider the GHG impacts and removals resulting from 1 year of operation. Not all relevant fluxes necessarily occur in the same year as operation. For example, leakage from storage (reversal) can occur over time after the operational year. We consider a removal timeframe of 100 years, which is generally considered the minimum timeframe to qualify for permanence.[60] We do not assert that this definition of permanence is sufficient, but addressing uncertainty related to long-term durability is beyond the scope of this paper, which focuses on intercomparison of flux accounting frameworks. Note that the geologic sequestration, biochar and aboveground mineralization cases included in our study are generally associated with long-term durabilities (hundreds to thousands of years).[61,62]

This illustrative study only considers major fluxes (emissions and removals) including those associated with raw materials production, transportation, and facility-level operations for each technology scenario. System boundaries and inclusion of these fluxes in accounting vary based on framework (Figure 1). To assess the embodied emissions in materials and energy consumed across the system supply chain, regardless of framework, we use conventional LCA methods and consider cradle-to-gate carbon intensities as determined by Agile-Cradle-to-Grave (Agile-C2G), a physical units-based input–output life-cycle inventory model.[63,64] For all technology scenarios, the impact of grid electricity consumption is evaluated by considering the US average grid GHG intensity. For real-world project-based accounting, case-specific carbon intensities for electricity should be used instead of a national average. Our analysis excludes impacts associated with facility construction, facility decommissioning, process material consumption (excluding raw materials and key materials), or maintenance/monitoring of long-term storage. A full evaluation of a CDR project, particularly for market purposes, must include these additional considerations.

Accounting metrics and frameworks

Gross storage

Gross storage is quantified by measuring atmospheric carbon that enters long-term storage. This metric accounts for direct leakages that occur after initial carbon capture/uptake up to the point of storage. For example, a DACS system may initially capture more CO_2 than it successfully injects into a reservoir for final storage. The quantity of injected CO_2 is considered gross storage. In some instances, initial carbon capture/uptake may occur over a duration longer than the operational timeframe considered (for this paper, 1 year). This is the case for the land-based mineralization scenarios: silicate mineral preparation and spreading completed in a single year of operation can result in gradual CO_2 mineralization that occurs over the course of multiple years. For these scenarios, gross storage includes all atmospheric carbon that enters storage over the removal timeframe (for this paper, 100 years). Gross storage excludes leakage from durable storage (reversal emissions), which is accounted for separately.

Activity-level LCA and net carbon benefit

For activity-level LCA, the narrowest possible system boundaries around the CDR intervention are applied. The scope of this accounting framework lends itself to a consequential LCA approach evaluating the marginal impact of implementing the CDR activity relative to a baseline counterfactual. In some cases, the CDR intervention is the primary process at a facility and may generate co-benefits. In these cases, activity-level LCA includes downstream co-benefits. In other cases, the CDR activity is a downstream process within the primary facility (e.g. BiCRS scenarios with CCS). In these instances, activity-level boundaries are drawn within facility operations and emissions or co-benefits generated upstream of the CDR activity are not included in activity-level LCA. Figure A2-1 in the Supplementary Information (Section 7, Appendix 2) visualizes these two example configurations for CDR systems and summarizes the carbon and GHG fluxes included in activity-level LCA as applied in this study.

For purpose-built or purpose-grown operations, all activities and associated emissions are included in the system boundaries for analysis as in the examples involving DACS, purpose-grown switchgrass for pyrolysis and purpose-excavated rock for mineralization. For CDR interventions that use wastes generated by another production system (e.g. waste CO_2 from a biorefinery, corn stover from corn farms, manure from dairy operations, tailings from a mining operation) as a feedstock or raw material, the activity-level boundary begins at feedstock collection, not feedstock production. For example, consider a BECCS facility: the activity-level boundary is around the CCS unit (the CDR activity) and the raw material is burden-free, biogenic waste CO_2. Additionally, in some cases like this, energy that is produced by a system upstream of the activity-level boundary is consumed by the CDR activity. In these cases, to maintain a consequential LCA approach, we evaluate the impact of activity-level energy consumption using average carbon intensities for the production in the US.

The counterfactual for activity-level LCA reflects current practices in the absence of a given CDR intervention. It assumes that prerequisite production systems which enable the CDR intervention will exist if their primary purpose is not CDR (e.g. corn farm that provides corn stover to a CDR intervention still operates and produces corn stover regardless of CDR). LCA differentiates between greenfield and brownfield development. Purpose-built operations and greenfield development are fully evaluated while LCA of brownfield development does not include penalties for existing infrastructure and systems. For CDR activities that use waste materials, the counterfactual includes waste management treatment from which waste is diverted. For instance, the counterfactual fate for biogenic, waste CO_2 (e.g. from a biorefinery or pulp mill) is direct emission to the atmosphere. For CDR activities that are multifunctional (i.e. generate co-products), the counterfactual includes conventional production of those co-products. Carbon benefits from waste diversion, co-product generation and any other activities that reduce emissions relative to the counterfactual (e.g. biochar application that reduces N_2O emissions from agricultural soil) are included as avoided emissions in LCA. In practice, LCA counterfactuals should be justifiable and case-specific.

Net flux framework and net removal

The purpose of the NFF is to quantify net carbon removal from the atmosphere. It is defined by expansive boundaries that begin with prerequisite systems upstream of the CDR intervention (i.e. feedstock or raw material production systems) and end with durable carbon storage and associated maintenance and monitoring activities (Figure A2-1, Appendix 2, Supplementary Information). All raw material production emissions are included in this accounting framework regardless of whether the feedstock is purposefully produced or generated as a waste/byproduct from another production system. For instance, in addition to collection and delivery impacts, agricultural residues are allocated the full impact of the associated farming operation including land use change. In rare cases, there are materials that undergo a transformative use phase for non-CDR market reasons before use as a “waste” feedstock for CDR (e.g. used cooking oil). The additional emissions burden of the use phase is not included in the embodied emissions of the material (e.g. used cooking oil does not have a higher embodied carbon intensity than unused cooking oil on a carbon content basis). The only feedstocks that are not associated with production burdens are “true wastes,” materials for which the original producer has an extremely weak or nonexistent economic linkage with the value of the material. In other words, increasing the value of the "true wastes" does not significantly benefit the original producer of these materials (e.g. municipal wastes, wastewater treatment sludge, thinnings from forest management for wildfire prevention). Downstream processing of non-CDR products from prerequisite systems is not included in the NFF (or LCA). For instance, consider a BECCS facility that uses corn stover to generate electricity and captures waste CO_2 for capture and long-term storage. All operations and associated impacts from the corn farm up until the point of corn and corn stover separation are included in the accounting for the NFF. Downstream processing or use of corn past this point is not included.

To distinguish between removals and other carbon benefits, the NFF does not include accounting of avoided emissions based on a current-day counterfactual. The counterfactual for the NFF is no CDR project or prerequisite production systems that enable the CDR (e.g. if the feedstock is waste CO_2 from a biorefinery, the counterfactual is no biorefinery; if the feedstock is almond hulls, the counterfactual is no almond production at all; if the feedstock is dairy manure, the counterfactual is no cows; if the feedstock is mine tailings from a recent operation, the counterfactual is no mining operation at all). The counterfactual does not include current practices or production systems (i.e. it makes no assumptions about demand for specific products), but it does assume that sustainable human life exists (e.g. municipal waste and sewage are generated, forests are sustainably managed). There is no differentiation between greenfield and brownfield development.

While the long-term goal of CDR may be to compensate for “hard-to-abate” emissions in addition to legacy emissions, there is uncertainty regarding which emissions are and will continue to be “hard-to-abate” in the future. Dufour-Décieux et al. define “hard-to-abate” emissions as those that are associated with a higher cost of abatement than direct air capture and storage.[65] A definition based on current market prices does not lend itself to unambiguous CDR accounting and therefore, the NFF makes no additional provisions for avoiding “hard-to-abate” emissions and purely evaluates the removal potential of legacy emissions (CO_2 in the well-mixed atmosphere).

Temporal limitations

Both activity-level LCA and the NFF struggle to capture time-dependent effects of CDR solutions. For example, an engineered CDR system can have initial emissions that occur during construction, recurring emissions related to maintenance, continuous emissions associated with operation (including embodied emissions), and reversal emissions that occur after storage. While not included in our simplified analyses, construction emissions can be allocated to the first year of a CDR project or amortized over the expected lifetime of the project or facility. Frontloading such emissions in a market context can restrict the initial profitability of new projects. If such emissions are allocated to the project over its expected lifetime, risk is introduced, particularly if the project must be decommissioned earlier than anticipated. There can also be variations in the timing of storage and removals. For instance, consider the land-based mineralization examples: the reaction of atmospheric CO_2 with prepared minerals to form stable carbonates from a single year of operation can occur over the course of multiple years. Removals and reversal emissions that occur in the future must be modeled and are associated with uncertainties. Modeling of reversal emissions can be particularly contentious since the long-term durability or reversal risks of many carbon storage sources are not well understood.[63,64] Future studies can explore a wider set of case studies by incorporating temporal considerations and different approaches for payments.

Technology scenarios

Direct air capture and storage

Direct air capture (DAC) systems capture CO_2 from ambient air which can be used for products or stored underground in a geologic reservoir (DACS). While use of captured carbon in long-lived products is technically viable, uncertainties regarding durability during use and end-of-life of products make geologic storage a more attractive and currently relevant option for reliable CDR.[66] This paper considers two DACS scenarios: a solvent-based system and a sorbent-based system. For the purposes of our analysis, we consider energy-related emissions, embodied emissions in key material inputs (i.e., solvent or sorbent), and carbon storage reversal risks from these two example systems. We do not consider impacts associated with construction, equipment, economic leakage or measurement, reporting and verification (MRV) to maintain comparability with other scenario results. Process input output data for both scenarios is adapted from Hanes et al. (2026) and related previous work from Qiu et al. (2022) (Table 1).[44,67]

For the solvent-based example, natural gas is combusted on-site and all associated emissions are captured and stored. Stored emissions from the combustion of natural gas are not included in "initial carbon storage" which only reflects CO_2 that is atmospheric in origin (versus fossil-based).

Table 2. Facility-level input output data for DACS scenarios adapted from Hanes et al. (2026)[44]

	DACS 1	DACS 2
Facility-level operations	Solvent-based direct air capture and storage	Sorbent-based direct air capture and storage
Facility-level net annual inputs		
$CaCO_3$ (kg/y)	7.69E+03	-
KOH (kg/y)	7.88E+06	-
Amine-functionalized polymer sorbent (kg/y)	-	4.31E+07
US-average electricity (kWh/y)	4.52E+08	9.71E+08
Natural gas (MJ/y)	7.05E+03	-
Facility-level net annual outputs		
Initial carbon storage (tonnes/y)	8.00E+05	6.00E+05

For carbon storage reversal, we adopt an annual leakage rate of 0.003% of stored CO_2, reflecting the current best estimate for long-term geologic storage integrity.[68,69] Empirical assessments of storage security and modeling work have demonstrated that well-sited and managed geologic storage reservoirs can provide stable and durable CO_2 containment over millennial timescales, with minimal expected leakage risk relative to total stored volume.[68,69]

The two DACS examples are similar and from a carbon accounting perspective, relatively simple to evaluate: they are purpose-built and have a single functionality (i.e. no co-products or economic co-benefits). Because these are purpose-built systems for which the primary raw material is freely available ambient air, activity-level and expansive system boundaries are the same. This is always the case for DACS however DAC systems do not have to involve geologic sequestration. Such systems can use captured CO_2 to make long-lived products (e.g. cement); if these products are truly durable and do not emit carbon back to the atmosphere during a desired removal timeframe, these systems may qualify as “CDR.” If these products provide a functional or economic benefit beyond CDR (as is the case for cement), the system can be considered as multifunctional. However, direct air capture for product generation is not currently especially relevant compared to DACS in CDR markets.[43] For this reason, the scope of this paper’s analysis is limited to DACS and includes two scenarios which vary process methods.

Biomass carbon removal and storage

BiCRS systems leverage biological carbon fixation processes to capture atmospheric carbon in biomass and then employ a variety of storage mechanisms to achieve long-term removal. These systems, unlike DACS, can involve complex feedstocks and produce non-CDR co-benefits leading to ambiguous LCA counterfactuals. This paper considers 5 BiCRS scenarios: corn-to-ethanol biorefinery with CCS, pulp mill with CCS, bioelectricity production and CCS (BECCS) using sawmill residues, BECCS using corn stover, and switchgrass pyrolysis for biochar production. All of these scenarios represent multifunctional systems that produce non-CDR benefits and/or use waste feedstocks and therefore have varying system boundaries under the NFF and activity-level LCA (Figure 1). In all BiCRS scenarios, the only transportation considered in our illustrative analyses is transportation of raw materials to the primary facility. For this, we use a general distance assumption of 80 km for all scenarios.

The first four BiCRS scenarios involve CCS units that capture biogenic CO_2 waste and inject it underground for long-term storage. In these cases, the activity-level boundary is drawn around the CCS units and only accounts for the energy costs of CCS, while expansive system boundaries include accounting of upstream activities that produce the captured biogenic CO_2 (Figure 1). For the first scenario, expansive system boundaries include ethanol production at a biorefinery and upstream corn cultivation. For this example, we consider facility-level input output data for a corn-to-ethanol biorefinery with CCS to capture emissions from fermentation from Dees et al. (2023) (Table 2).[45] For corn cultivation in the first and fourth BiCRS scenarios, we consider input-output data, soil emissions data and land use change impacts from the GREET model (Table A2-1, Appendix 2).[70] The CCS unit for this first example scenario is powered by grid electricity.

Table 3. Simplified facility-level input output data for BiCRS scenarios

	BICRS 1[45]	**BICRS 2[71]**	**BICRS 3**	**BICRS 4**	**BICRS 5[72]**
Facility-level operations	corn-to-ethanol biorefinery	pulp mill	BECCS	BECCS	pyrolysis facility
Activity-level operations	CCS	CCS	CCS	CCS	pyrolysis facility and upstream switchgrass cultivation
Facility-level net annual inputs					
Raw material (tonnes)	3.65E+05 (corn)	4.64E+06 (wood)	2.77E+05 (sawmill residues)	2.86E+05 (corn stover)	8.41E+04 (switchgrass)
US-average electricity (kWh)	1.06E+08	-	-	-	-
Natural gas (MJ)	3.44E+08	-	-	-	4.88E+06
Heavy fuel oil (kg)	-	2.80E+07	-	-	-
Facility-level net annual outputs					
Biochar (wet tonnes)	-	-	-	-	2.42E+04
Initial carbon storage (tonnes)	1.03E+05	8.00E+05	4.31E+05	3.53E+05	5.60E+04
US-average electricity (kWh)	-	1.76E+08	2.64E+08	2.64E+08	-
Other coproducts	• ethanol (3.26E+09 MJ) • DDGS (1.03E+05 t) • corn oil (2.79E+05 t)	• pulp (3.12E+07 t) • crude tall oil (1.76E+05 kg)	none	none	surplus heat (4.87E+08 MJ)
Activity-level annual inputs					
US-average electricity (kWh)	3.24E+07	7.28E+08 (generated and consumed on-site)	1.08E+08 (generated and consumed on-site)	1.08E+08 (generated and consumed on-site)	same as facility-level

Activity-level annual outputs					
	only output is facility-level carbon storage	only output is facility-level carbon storage	only output is facility-level carbon storage	only output is facility-level carbon storage	all outputs are same as at facility-level

For the second BiCRS scenario, expansive system boundaries begin with wood harvesting from sustainably managed forests (i.e. direct emissions from harvesting operations are included but emissions associated with land use change are not). This wood is used as a feedstock for a pulp mill which produces pulp, electricity, crude tall oil, and waste CO_2. The CO_2 is captured by on-site CCS which consumes a portion of facility-generated electricity. We use facility-level data for a standalone kraft pulp mill from Onarheim et al. (2017)[71] and upstream data for wood harvesting assuming shelterwood logging (70% cut) from Zhang et al. (2016).[73]

The third and fourth BiCRS scenarios involve bioenergy carbon capture and storage (BECCS) facilities. In these scenarios, expansive system boundaries include the BECCS facility and upstream feedstock production (sawmill operations in the third scenario and corn farming in the fourth scenario). We model annual feedstock demand and CO_2 sequestered for a 50 MW BECCS facility with an 85% annual capacity factor (see Appendix 2 for detailed calculations and assumptions). For the third scenario, upstream data related to sawmill operations comes from Khatri et al. (2025).[74] For the fourth scenario, we use the same corn cultivation data as the first BiCRS scenario and assume that the harvestable fraction of corn stover is 30%.[50]

The last BiCRS scenario reflects a purpose-built system in which switchgrass is intentionally cultivated for pyrolysis and biochar production so activity-level and expansive, system-level boundaries are the same. In both cases, boundaries begin with switchgrass cultivation and end with biochar application. Scenario data is adapted from Robert et al. (2010)[72] which describes a pyrolysis system configured for biochar production for CDR (versus for fuel production) where the pyrolysis temperature is 450°C and the throughput is 10 tonnes of biomass per hour. Gas and tarry oils are also generated alongside biochar, but are combusted for on-site heat generation. Surplus heat is generated, but we use a conservative approach and do not assume that this heat will offset fossil-based heat consumption. We use the same assumptions from Roberts et al. (2010) regarding carbon stored in biochar: the carbon content of biochar is 63%, 80% of carbon in biochar is stable and the remaining 20% is labile and emitted back to the atmosphere in the first few years after application.[72] For this study, we include any carbon lost from the biochar after application in “reversal emissions.” Biochar application can have additional carbon benefits: reducing N_2O emissions from soils (0.394 kg of N_2O emissions avoided per tonne of biochar applied) and displacing emissions-intensive fertilizers.[72] In this study, we account for reduced soil emissions, but we do not assume that biochar will offset fertilizer use which depends on local farming practices.

Land-based mineralization

Land-based mineralization CDR projects leverage the ability of calcium- and magnesium-rich silicate minerals to react with CO_2 to form stable carbonates (Meyers et al. 2019). Unlike DACS or BiCRS, which are characterized by their CO_2 capture mechanisms (engineered extraction from ambient air or biological fixation, respectively), land-based mineralization solutions are characterized by their storage mechanism: stable mineral carbonates. Calcium- and magnesium-rich silicate minerals can react with CO_2 in either ambient air or concentrated CO_2 streams (e.g. CO_2 from DAC or CCS) to form stable carbonates underground (in-situ mineralization), above-ground (enhanced rock weathering), or in long-lived products like cement (ex-situ mineralization). The raw materials for these systems can be purposefully-mined rock or waste streams from mining and mineral processing operations.

For this paper, we consider two examples of purpose-built mining for enhanced rock weathering from a 2026 report from Lawrence Livermore National Laboratory which explored the CDR potential at a former asbestos mine in California.[75] We use the site-specific assumptions and other relevant data from this report as documented in Table 3. This includes assumptions about the baseline CO_2 mineralization rate at the site without further intervention (counterfactual carbon storage) and land use change. For emissions associated with land use change, we consider the facility lifetime to allocate a portion of these impacts to a single year of operation. In both of the scenarios, rock containing both brucite and chrysotile is intentionally excavated and prepared for CDR purposes. In the first scenario, excavated rock is laid out in controlled greenhouses for CO_2 exposure and all equipment is electrified. In the second scenario, prepared materials are tilled into managed lands directly next to the excavation site for exposure to ambient air. For this scenario, we assume that mining, transport, and mixing equipment is diesel-powered while grinding equipment is powered by electricity. Because it does not involve building new infrastructure (greenhouses), the in-situ tilling method may be more likely to be adopted by existing mining operations as a low-effort option to reduce their carbon impact by making use of mineral-rich mine tailings.

Table 4. Facility-level input output data and other relevant data for land-based mineralization scenarios adapted from Schmidt et al. (2026)[75]

	Mineralization 1	Mineralization 2
Facility-level operations	Greenhouse method and electrified equipment	Tilling method and diesel-based equipment

Facility site characteristics		
Counterfactual carbon storage (tonnes/year)	-3.26E+06	-3.26E+03
GHG emissions from land use change	-2.54E+04	-2.54E+04
Facility life time (years)	30	30
Facility-level net annual inputs		
US-average electricity (kWh/yr)	3.33E+07	3.60E+05
Diesel (MJ/yr)	0.00E+00	3.45E+07
Facility-level net annual outputs		
Extracted mineral mass (tonnes/yr)	2.58E+06	4.72E+05
CO_2 mineralization potential (tonnes CO_2/tonne rock)	1.78E-01	2.20E-02
Initial carbon storage (tonnes/yr)	4.60E+05	1.04E+04

Similarly to DACS, the land-based mineralization scenarios in this analysis also represent purpose-built, single-function examples but this is not always the case for CDR mineralization systems. These solutions do not need to be purpose-built: instead of excavating rock solely to use as a raw material for CDR, projects can use silicate minerals in mine tailings or other waste streams from mining/mineral processing activities. It is important to note that mineralization of CO_2 into stable carbonates is only considered CDR if the CO_2 is atmosphere in origin. If a slag stream from a mineral processing facility (e.g. steelmaking facility) mineralizes CO_2 from fossil-based flue gas generated by the facility (e.g. from a fossil-powered blast furnace), the system only has the potential to mitigate emissions from mineral processing and has no potential for true CDR.

Resource availability

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Corinne D. Scown (CDScown@lbl.gov).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Relevant data is included in the main manuscript and Supplementary Information files.

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Author contributions

Conceptualization, S.N., E.S., K.M., S.B., C.S.; Data curation, S.N., C.D.; Formal analysis, S.N., C.D.; Methodology, S.N., C.S.; Project administration, S.B., C.S.; Visualization, S.N.; Writing – original draft, S.N., C.S.; Writing – review & editing, S.N., E.S., K.M., S.B., C.S.

Declaration of interests

The authors have no competing interests to declare.

Supplementary Information

Document S1 contains Appendix 1 (Protocol Intercomparison: Detailed Outcomes):
DACS Protocols are reviewed in Tables A1-1 through A1-12.
BiCRS Protocols are reviewed in Tables A1-13 through A1-25.
BECCS Protocols are reviewed in Tables A1-26 through A1-33.
Land-Based Mineralization Protocols are reviewed in Tables A1-34 through A1-46.
Enhanced Rock Weathering Protocols are reviewed in Tables A1-47 through A1-58.

Document S2 contains Appendix 2 (Data and Modeling Assumptions):
Data for assessing upstream impacts are included in Tables A2-1 through A2-3.
BECCS Modeling is described in Section 2 and includes Table A2-4.
Summaries of assumptions for each scenario are included in Tables A2-5 through A2-10.

LCA data for material and energy inputs are described in Tables A2-11 and A2-12. Tabulated results for each scenario are included in Tables A2-13 through A2-18

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Appendix 1: Protocol Intercomparison: Detailed Outcomes

Accounting Methods Dictate Carbon Removal Credit Integrity and Outcomes

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1. Relevance and Summary

Most existing protocols from CDR registries tend to exist somewhere between activity-level LCA and the NFF. Protocols tend to use intermediate system boundaries, placing guardrails on activity-level LCA or creating allowances within frameworks similar to the NFF. Because most protocols occupy this middle ground, they are not necessarily grounded in a single coherent framing.[1] Guardrails can sometimes appear to be applied ad hoc, with the goal of preventing specific outcomes deemed undesirable.[1]

We review protocols, spanning a range of relevant technology classes of engineered CDR. This includes direct air capture and storage (DACS) protocols from Isometric[2] and the government of Canada,[3] varied biomass carbon removal and storage (BiCRS) protocols from Isometric,[4–7] Puro.Earth,[8,9] Verra,[10] Climate Action Reserve,[11] and Carbon Standards International,[12] bioenergy with carbon capture (BECCS)-specific protocols from Isometric,[13] Verra,[14] and Gold Standard,[15] enhanced rock weathering protocols from Isometric[16] and Puro.Earth,[17] and other varied, land-based mineralization protocols from Isometric,[18] Puro.Earth,[19] Verra,[20] and Gold Standard.[21]

The reviewed DACS protocols are generally aligned with the NFF, only crediting the carbon effectively stored underground for a given removal timeframe and applying a penalty equivalent to emissions from the DACS facility construction, operation, and maintenance. Isometric does allow for allocation of emissions to co-products, but in most DACS cases, this is not a substantial credit.[2] There is no substantial difference in quantified removal for DACS between activity-level LCA and the NFF. Variability in accounting results for DACS tend to stem from energy-related emissions accounting (i.e. impacts associated with electricity consumption).[22]

The most notable divergence from the NFF comes from the non-DACS protocols, many of which allow for burden-free accounting for inputs deemed waste products and/or allocation of emissions to co-products. These allowances create flexibility for CDR suppliers, but are inherently based on current day counterfactuals of existing supply chains. Over time, as other supply chains decarbonize and CDR becomes more relevant, these allowances can decrease and may reveal systems that do not achieve a net flux of CO_2 out of the atmosphere. In the context of DACS, these allowances may not be substantial, but when considering other CDR systems, this same perspective may incentivize behaviors that do not contribute to the long-term goals of CDR. Given the price premium that CDR currently commands over mitigation, there may be an incentive for both buyers and sellers of credits to leverage any methodological gray areas in LCA-based frameworks to classify mitigation activities as CDR.

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2. DACS Protocols

This review for DACS includes the following protocols:

- Isometric Direct Air Capture Protocol
- Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol

Tables that do not include a column for data source requirements indicate that the protocols did not specify any recommended or required data sources.

Note: Text in italics are directly taken from the standards/protocols. Footnotes indicate the specific section for each component in the respective protocol.

Table A1-1. Project siting and construction emissions

Protocol	Scope
Isometric	*Embodied emissions associated with equipment and materials manufactured for project establishment. Emissions related to construction and installation of the project site. Any embodied energy and transport emissions associated with surveys or feasibility studies required for establishment of the project site.*[1]
Government of Canada	None. The following emissions are excluded: *Production of construction materials, land clearing and soil carbon loss from construction of project facilities and infrastructure, construction of project facilities and infrastructure.*[2]

Table A1-2. DACS transportation emissions

Protocol	Scope	Data source requirement
Isometric	*Transport emissions associated with transporting materials and equipment to the project site. Electricity or fuel used for operation of a pipeline or similar non-mobile CO_2 transportation process maintenance of transportation infrastructure including maintenance, repair, replacement and refurbishment. Additionally, transport of consumables used for the operation.*[3] *Include all emissions associated with the fuel-cycle such as direct combustion of fuel as well as indirect upstream emissions, including*	Delivery of material input consumed at capture facility.[5]

[1] Isometric Direct Air Capture Protocol, section 7.1, table 1
[2] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 7, table 1.
[3] Isometric Direct Air Capture Protocol, section 7.1, table 1
[5] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 7, table 1.

	production and distribution of fuel or electricity. *Embodied life cycle emission factors must be used for vehicles and infrastructure produced, constructed, and utilized for the CO_2 removal project, and this must be calculated in addition to the Energy Usage or Distance-Based Methods.*[4]	
Government of Canada	Can be calculated using energy usage or distance-based methods. [6]	Emission factor for CO_2, CH_4, N_2O provided for fuels provided in the *Emission Factors and Reference Values document*[7]

Table A1-3. DACS energy (electricity and fuel) use emissions

Protocol	Scope	Data source requirement	Miscellaneous
Isometric	*The emissions associated with energy use must account for all operations that consume energy within the CDR project processes, through the usage of both electricity and fuel.* Electricity emission factors represent the life cycle of the fuel used to generate electricity and of the generator.[8]	If project is grid powered, use *DOE National Transmission Needs Study* emission factor for grid electricity. No specific emission factor source is required for projects with PPA, but factors must include generator and fuel. [9]	Differentiates accounting for facilities consuming under (non-intensive) and over 200 GWh (intensive). Annual volumetric matching for non-intensive facilities, hourly volumetric for intensive. Waste heat can be used as a burden free energy input. [10]
Government of Canada	Energy and fuel used to operate the capture process, transport infrastructure and operation of injection infrastructure. *Emissions associated with the extraction, processing and delivery of fossil fuels used on-site for the generation of heat, electricity and energy consumed by the*	*GHG consumption intensity emission factor for grid electricity from the project jurisdiction, or an emission factor for electricity procured through a power purchase agreement.*[12]	*If the proponent procures renewable energy for a project (e.g. for the operation of the capture facility), they must ensure and demonstrate that the renewable energy is additional, meaning the renewable energy is generated explicitly for the project and is not displaced*

[4] Isometric Transportation Emissions Accounting Module
[6] Isometric Transportation Emissions Accounting Module
[7] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, Equation 20.
[8] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[9] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[10] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[12] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, Equation 15.

	project[11]. Waste heat can be used as a burden-free input.		*and removed from the grid or pre-existing end users*[13]

Table A1-4. DACS operational and direct emissions

Protocol	Scope
Isometric	All emissions associated with the DAC and storage processes process, including use of consumables, maintenance of the equipment and infrastructure, waste processing. *Any intentional or unintentional release of emissions due to maintenance, emergency shutdown of equipment, faulty equipment, etc*. Any emissions incurred by the monitoring process, including sampling and surveys, need to be accounted for. Additionally, must account for embodied emissions of consumables and other miscellaneous emissions such as staff travel.[14]
Government of Canada	Operation of capture facility, transport infrastructure, and injection infrastructure. Embodied emissions of consumables and materials. Loss and disposal of consumables and materials. Vented and fugitive emissions (leaks) from injection infrastructure. The following emissions are **excluded**: Vented emissions at capture facility and fugitive emissions at capture facility. Vented emissions throughout transport infrastructure and fugitive emissions throughout transport infrastructure.[15]

Table A1-5. DACS end-of-life emissions

Protocol	Scope
Isometric	Anticipated end-of-life emissions including deconstruction and disposal of equipment and infrastructure.[16]
Government of Canada	Emissions associated with *Decommissioning of project facilities and infrastructure are* **excluded**. Emissions associated with the monitoring of storage in the reservoir need to be accounted for.[17]

Table A1-6. DACS counterfactual

Protocol	Scope

[11] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 7, table 1.
[13] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 6.4.2
[14] Isometric Direct Air Capture Protocol, section 7.1, table 1
[15] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 7, table 1.
[16] Isometric Direct Air Capture Protocol, section 7.1, table 1
[17] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 7, table 1.

Isometric	*The counterfactual of qualifying projects is typically considered to be zero.*[18]
Government of Canada	The counterfactual is zero.[19]

Table A1-7. DACS economic leakage (market-mediated impacts)

Protocol	Scope
Isometric	*For a DAC Project, market leakage emissions associated with the replacement of consumables used must be considered as a minimum. Project Proponents may also consider the impact of project operations on potential increased use of rare-earth materials for the production of sorbents, land use change, and increased strain on existing CO_2 transportation and storage infrastructure.* [20]
Government of Canada	*Since the baseline scenario of a project is the absence of the geological storage of direct air captured CO_2 within the project site, there is no leakage risk for projects under this protocol.*[21]

Table A1-8. DACS multifunctionality

Protocol	Scope
Isometric	Co-product allocation for coproducts.[22] Emissions for inputs considered waste products may be excluded.[23]
Government of Canada	*Since the baseline scenario of a project is the absence of the geological storage of direct air captured CO_2 within the project site, there is no leakage risk for projects under this protocol.*[24]

Table A1-9. DACS net removal calculation

Protocol	Net removal calculation
Isometric	The gross CO_2 stored, minus all project emissions, minus leakage emissions, minus the counterfactual (which is 0) [25]

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[18] Isometric Direct Air Capture Protocol, section 7.2
[19] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 8.1
[20] Isometric Direct Air Capture Protocol, section 8.2.3.4
[21] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 8.5
[22] Isometric GHG Accounting Module, section 6.1
[23] Isometric Direct Air Capture Protocol, section 7.1.1.3
[24] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 8.5
[25] Isometric Direct Air Capture Protocol, section 8.2

Government of Canada	Gross removals, minus all project emissions, minus the baseline removal (0) [26]

Table A1-10. DACS baseline definitions

Protocol	Baseline Definition
Isometric	*The baseline scenario for a DAC project assumes the activities associated with The Project do not take place and any associated infrastructure is not built.* [27]
Government of Canada	The baseline is zero[28].

Table A1-11. DACS storage durability, permanence, and timing of carbon removals.

Protocol	Durability and Permanence Requirements
Isometric	>1000 years[29]
Government of Canada	100 years[30]

Table A1-12. DACS additionality requirements

Protocol	Requirements
Isometric	Financial, Regulatory, Market Adoption and Environmental. [31]
Government of Canada	Regulatory[32]

3. BiCRS Protocols

Note: Text in italics are directly taken from the standards/protocols. Footnotes indicate the specific section for each component in the respective protocol.

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[26] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 8.4
[27] Isometric Direct Air Capture Protocol, section 7.2
[28] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 8.1
[29] Isometric Direct Air Capture Protocol, Summary
[30] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 10.2
[31] Isometric Direct Air Capture Protocol, section 6.4
[32] Government of Canada, Direct Air Carbon Dioxide Capture and Geological Storage Federal Offset Protocol, section 5

Table A1-13. BiCRS project siting and construction emissions.

Protocol	Scope	Data Source Requirements
Isometric	Surveys and feasibility studies. Procuring and transporting material to project sites. Installation and construction, including groundwork and waste processing activities. Direct land use changes due to project establishment.[33] Account for all equipment[34] *Use cradle-to-grave emission factors*.	None specified
Puro	Carbon emitted in the fabrication and construction of infrastructure and/or equipment assets, and in direct land-use conversion associated with the production facility and supporting infrastructure.[35] Shall be cradle-to-grave, including all steps from material extraction to waste disposal.	EN 15804+A2, EN 15978, or ISO 21930:2017. Alternatively, recent monetary emission factors (e.g., kg CO_2e per USD spent) may be used as a proxy for estimating embodied emissions based on capital expenditure. Direct land use change shall be quantified using either the default values for land conversion available in the IPCC Guidelines for National Greenhouse Gas Inventories 39 (IPCC, 2006) (IPCC, 2019) (Tier 1), or country-specific values (Tier 2), or data specific to the project (Tier 3).)[36]
Verra	Do not account for establishment emissions[37].	N/A
CAR	Transportation of equipment to the facility.[38]	None specified
CSI	Manufacture and transportation of kiln, pump for quenching water, blender, and equipment used for application.	20 kg CO_2/ton biochar for all establishment emissions, provided all transportation is 100 km or less.[39]

Table A1-14. BiCRS transportation emissions.

Protocol	Scope	Data Source Requirements

[33] Isometric Biochar Production and Storage, section 8.5.1
[34] Isometric Embodied Emissions Accounting, section 2.0: system boundaries: https://registry.isometric.com/module/embodied-emissions/1.0#system-boundaries
[35] Puro Biochar Methodology, section 7.4 Quantification of embodied emissions.
[36] Puro Biochar Methodology, section 7.4 Quantification of embodied emissions.
[37] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 5: Project Boundaries
[38] Climate Action Reserve, US and Canada Biochar Protocol, section 4, table 4.1
[39] Standard for Carbon Sink Certification for artisan Biochar production, section 13: Emission Portfolio, Carbon Leakage, and Margin of Security.

Isometric	Include all emissions associated with the fuel-cycle such as direct combustion of fuel as well as indirect upstream emissions, including production and distribution of fuel or electricity. Embodied life cycle emission factors must be used for vehicles and infrastructure produced, constructed, and utilized for the CO_2 removal project, and this must be calculated in addition to the Energy Usage or Distance-Based Methods.[40]	None specified
Puro	Direct emissions only for transportation of: Biomass to production facility. Biochar from production facility to final point of use. [41]	ISO 14083:2023 or GLEC Framework v3.1
Verra	Direct emissions only for transportation of: Feedstock from production to processing facilities. Biochar from processing facility to end-use application site. Only for transportation distances over 200 km.[42]	Can be calculated measuring fuel consumption and using an emission factor for that fuel or *using conservative default values* based on the quantity of freight transported, the distance and the class of vehicle[43]
CAR	Direct emissions only for transportation of: Biomass feedstock from source to processing facility. Processed biochar to end use facility. [44]	*Transportation emissions may be calculated based on fuel records, if available, or on transportation mode, mass of feedstock transported, and distance traveled. Default emissions factors for either approach are provided in the Biochar CRT Calculation Tool*[45]
CSI	Direct emissions only for transportation of: Feedstock from production to processing facilities. Processed biochar to application sites. Only for transportation distances over 100 km.[46]	

[40] Isometric Transportation Emissions Accounting Module
[41] Puro Biochar Methodology, section 7.2 Scope of Project Emissions
[42] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.3
[43] CDM Tool 12: Project and leakage emissions from transportation of freight: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-12-v1.1.0.pdf
[44] Climate Action Reserve, US and Canada Biochar Protocol, section 4, table 4.1
[45] Climate Action Reserve, US and Canada Biochar Protocol, section 5.2.1.2
[46] Standard for Carbon Sink Certification for artisan Biochar production, section 13: Emission Portfolio, Carbon Leakage, and Margin of Security.

Table A1-15. BiCRS energy (electricity and fuel) use emissions

Protocol	Scope	Data Source Requirements	Miscellaneous
Isometric	*The emissions associated with energy use must account for all operations that consume energy within the CDR project processes, through the usage of both electricity and fuel.* Electricity emission factors represent the life cycle of the fuel used to generate electricity and of the generator.[47]	If project is grid powered, use DOE National Transmission Needs Study emission factor for grid electricity. No specific emission factor source is required for projects with PPA, but factors must include generator and fuel and may use source *factors such as GREET, Ecoinvent and USLCI*.[48]	Differentiates accounting for facilities consuming under (non-intensive) and over 200 GWh (intensive). Annual volumetric matching for non-intensive facilities, hourly volumetric for intensive. Waste heat that cannot be recovered for other purposes is eligible. [49]
Puro	Electricity and fuel consumption to produce biochar as well as end application activities.[50]	Must use an emission factor that is geographically relevant and accounts for whole generation life cycle. No specific data source required.	Can use RECs to claim reduced GHG intensity if they are in the same grid region and must match low-carbon energy reported by project.[51]
Verra	Electricity and fuels used for pre-treatment of feedstock. Electricity and fuels used for the purpose of pyrolysis. *If the energy source is renewable, emissions are zero.*[52]	Emission factor used if using grid-connected electricity and for fuel use a fuel specific emission factor. [53]	Additionally, leakage emissions associated with increased electricity compared to the baseline need to be accounted for. [54].
CAR	Electricity, fuel and heat use for all project activities[55]	Use eGRID for grid-connected facilities and US EPA GHG Emissions Hub for non-grid connected facilities.[56]	
CSI	Energy emissions associated with biomass cultivation, harvesting crushing, pyro-gas combustion, milling,	No specific data source required.	As the biochar production in Kon-Tiki kilns does not consume any electricity or fuel, the carbon footprint of

[47] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[48] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[49] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting
[50] Puro Biochar Methodology, section 7.2 Scope of Project Emissions
[51] Puro Biochar Methodology, section 7.1.10 and 7.1.11
[52] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.2.2.1
[53] CDM Tool 5: Baseline, Project and or leakage emissions from electricity consumption and monitoring of electricity generation: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v3.0.pdf
[54] CDM Tool 5: Baseline, Project and or leakage emissions from electricity consumption and monitoring of electricity generation: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v3.0.pdf
[55] Climate Action Reserve, US and Canada Biochar Protocol, section 4, table 4.1
[56] Climate Action Reserve, US and Canada Biochar Protocol, Equation 5.10

	blending and soil or material incorporation. *As the biochar production in Kon-Tiki kilns does not consume any electricity or fuel, the carbon footprint of the biochar production with this technology is very low*. Electricity used by the CDR technology itself is excluded from the scope if using this technology. [57]		the biochar production with this technology is very low.

Table A1-16. BiCRS operation and direct emissions

Protocol	Scope	Data Source Requirements
Isometric	Direct emissions from: Biomass feedstock processing, pyrolysis or other processes. Maintenance of the project site. Use of consumables including upstream emissions. Waste processing and disposal. Bio-oil/biochar processing and characterization (sampling). Temporary storage of processed biomass Bio-oil/biochar storage and injection. Sampling and all other MMRV activities. Staff travel and surveys. [58]	None specified
Puro	Direct emissions from: Biomass handling, drying and chipping. Operation of the pyrolysis reactor and post-pyrolysis processes, biochar quenching and handling. Biochar end use or application[59]	None specified
Verra	Direct emissions from: Applying the biochar in soil or non-soil applications. [60] Exclude all pyrolysis emissions from facilities that:	None specified

[57] Standard for Carbon Sink Certification for artisan Biochar production, section 13: Emission Portfolio, Carbon Leakage, and Margin of Security.
[58] Isometric Biochar Production and Storage, section 8.5.2 and table 1
[59] Puro Biochar Methodology, section 7.3 Quantification of operational emissions
[60]VM0044 Biochar Utilization in Soil and Non-Soil Application, section 5, table 2

	Do not emit pyrolytic greenhouse gases Recover at least 70% of the heat produced. Have pollution controls such as thermal oxidizers to meet regulatory thresholds. Measure and report production temperature. Include methane emissions only from pyrolysis facilities that do not meet one or more of the above conditions	
CAR	Direct emissions from: Feedstock drying and processing. Thermochemical conversion, including methane. Embodied emissions from: All fuel used (use a fuel emissions factor when using fuel). [61]	None specified
CSI	Direct methane emissions only from pyrolysis.	30 kg of CH_4 per ton of biochar for Kon-Tiki kilns. Pro rata factor for TLUD stoves[62] based on feedstock and biochar masses and LLVs.

Table A1-17. BiCRS end-of-life emissions

Protocol	Scope
Isometric	*All emissions associated with activities that are anticipated to occur after the Reporting Period but are directly or indirectly related*. Sampling for MRV beyond the injection phase. Deconstruction of the plant. Waste handling at the end of the project lifetime. [63]
Puro	LCA factors must account for downstream emissions for all processes. [64]
Verra	Emissions associated with biochar application, however no accounting for emissions associated with decommissioning and waste disposal.[65]
CAR	Emissions from end application of biochar accounted for. However, no emissions from plant decommissioning or ongoing monitoring accounted for. [66]

[61] Climate Action Reserve, US and Canada Biochar Protocol, section 4, table 4.1
[62] Standard for Carbon Sink Certification for artisan Biochar production, section 14: Methane emissions.
[63] Isometric Biochar Production and Storage, section 7.1, table 1 and section 8.5.3
[64] Puro Biochar Methodology, section 7.1 General life cycle assessment requirements
[65] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 5
[66] Climate Action Reserve, US and Canada Biochar Protocol, section 4, table 4.1

CSI	Not addressed.

Table A1-18. BiCRS counterfactuals definitions and emissions

Protocol	Scope	Approach	Miscellaneous
Isometric	Counterfactual Storage: CO_2 that would have been permanently stored in the biomass in the absence of the CDR project. Known as ineligible biomass. Biomass, whose counterfactual fate is being released in the next 15 years is eligible biomass.[67]	*If the counterfactual fate of the biomass includes the stored biogenic C being emitted as GHGs with a GWP100>1, the total biomass eligible is equal to the minimum of:* *(1) the CO_2e (evaluated at GWP100) of counterfactually released GHGs emitted within 15 years* *(2) the total stored CO_2 in the biomass minus the CO_2 in biomass that would not have counterfactually been released within 50 years.* *Landfilled wood is not an eligible feedstock, unless the Project Proponent can demonstrate the counterfactual fate would release all stored biogenic carbon within 15 years.* *Feedstocks that are sourced through government managed or funded wildfire mitigation or restoration activities will be assigned a counterfactual storage value of 0.* *Applicable to non-forestry feedstocks: The biomass feedstock was not grown for the purposes of energy production and does not have a likely counterfactual energy production use.*[68]	Note: Biomass that decays but can still lead to durable storage e.g.: corn stover decay leading to increase soil C content may still be ineligible. Proponent must show sourcing practices have no impact on durable carbon stocks.
Puro	Counterfactual emissions for eligible feedstock are 0.[69]	*Mitigation of ecological leakage relating to negative effects on the nearby land and ecosystems surrounding the areas where biomass is sourced from is achieved if the biomass used is demonstrated to be eligible as per the Puro Biomass*	None specified.

[67] Isometric Biomass Feedstock Accounting Module, section 2.2 Table 5
[68] Isometric Biomass Feedstock Accounting Module, section 2.2 Table 5 and Table 6.
[69] Puro Biomass Sourcing Criteria and Puro Biochar Protocol section 8.2.2

Protocol	Scope	Approach	Miscellaneous
		Sourcing Criteria. This leakage source can be set to zero in the quantification. [70]	
Verra	Counterfactual fate is the feedstock would have otherwise decomposed or burned for non-energy purposes. *Emission avoidance as zero following a conservative scenario.*[71]	None specified.	None specified.
CAR	*There would be emissions expected to be associated with the fate of feedstock biomass in the absence of the project, it is conservative to assume a value of zero 0.*[72]	*Although some carbon in eligible waste and by-product feedstock types may be sequestered under the baseline scenario, the vast majority of such carbon combusts or decomposes over relatively short time scales.*[73]	None specified.
CSI	Depending on the alternative fate of feedstock, there can be a credit for avoided methane emissions. [74]	None specified.	None specified.

Table A1-19. BiCRS economic leakage (market-mediated impacts)

Protocol	Scope	Approach
Isometric	For biomass projects, replacements emissions (to compensate for biomass that was serving another purpose) are the minimum leakage. Projects that would lead to ecological leakage associated with land use change are ineligible. [75]	Replacement emissions: The addition of replacement emissions associated with energy, embodiment and transportation of new feedstock serving a market need the CDR project could be displacing. Cases where replacement emissions are exempt are the following: *If the feedstock currently serves no purpose, such as mill residues in a stockpile or forest residues sitting on the forest floor, there are deemed to be no replacement emissions.*

[70] Puro Biochar Protocol section 8.2.2
[71] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.1.1
[72] Climate Action Reserve, US and Canada Biochar Protocol, section 5.1
[73] Climate Action Reserve, US and Canada Biochar Protocol, section 5.1
[74] Standard for Carbon Sink Certification for artisan Biochar production, section 14.6 and 14.7
[75] Isometric Biomass Feedstock Accounting Module, section 3.2

Protocol	Scope	Approach
		For project feedstock usage above the percentage of what is theoretically possible to use for a given purpose (the 'Sustainable Use Rate') the feedstock would be considered true waste and therefore not require calculation of replacement emissions. For environmental services replacement emissions, the mass of replacement can be used to calculate the emissions. For example, the fertilizer capacity from feedstock that needs to be replaced can be calculated by sampling the amount of nitrogen, phosphorus and potassium in each batch. Amount in counterfactual scenario must account for replacing same amount of NPK. [76]
Puro	Must account for leakage emissions for both ecosystem changes and market-shifting activity. Identify leakage sources: land use changes due to project activities and biomass sourcing. Market activity shifting in the agriculture and forestry sectors relating to the use of feedstock or use of land. [77]	Leakage must be calculated depending on the type of facility: New facility – replacement emissions from material and energy due to the use of feedstock or land that were used for other purposes. Retrofit facility – Replacement emissions from reduced bioenergy or biomaterial output. Charcoal repurpose – Replacement emissions from diverting charcoal Ecologic Leakage must be mitigated by defining a land area of impact and showing that activities won't significantly impact land coverage, local hydrology and the carbon stocks. If biomass meets sourcing criteria, leakage for sourcing is considered 0 for both ecologic and market leakage. Market leakage must be mitigated when using a nutrient-rich feedstock, by showing biochar is applied to soil or showing that there is an oversupply of nutrient rich feedstock in the area. In a retrofit facility, by showing sourcing does not impact energy or material outcome. In a charcoal repurpose, if no reductions in the charcoal volume used for other purposes are observed. For sources not mitigated, market leakage calculated as the net change in product between project and baseline, multiplied by a representative emission factor to that service. Ecologic leakage is calculated as the quantity

[76] Isometric Biomass Feedstock Accounting Module, section 3.2
[77] Puro Biochar Protocol, section 8.

Protocol	Scope	Approach
		of feedstock with high risk of indirect land use change, multiplied by its lower calorific value multiplied by an indirect land use change factor and multiplied by an attribution factor. Protocol provides value for indirect land use change factors.[78]
Verra	Leakage due to activity shift is considered 0, as purposefully grown biomass is not allowed. Leakage due to diversion is considered negligible as only waste feedstocks or those that would been combusted are eligible. Thus, no economic or ecological leakage accounted for.[79]	Not specified.
CAR	Applies for purpose grown feedstocks and those diverted from bioenergy.[80]	Since purpose grown are only eligible in marginal lands, no indirect land use emissions are considered and thus leakage is considered 0. If diversion from bioenergy, no leakage is accounted for if a reduction in energy production from the bioenergy facility is below 5%, however, for amounts higher than this percentage, the replacement emissions must be calculated using electrical grid emissions from the biochar facility location.[81]
CSI	Not considered	Not specified.

Table A1-20. BiCRS multifunctionality

Protocol	Scope
Isometric	Embodied emissions for inputs considered to be waste can be excluded from the GHG accounting.[82] In terms of co-product allocation, most conservative approach is CDR products will take full burden. Where processes are physically separable, processes that do not contribute to CDR can be excluded from the boundary.Where processes are not physically separable, the substitution method may be used to account for avoided emissions associated with the production of a co-product, only if these emissions are deemed *residual* or *hard-to-abate.* If co-product leads to CDR credit, allocation should be done based on carbon mass balance.[83] *Emissions allocation may be undertaken based on energy content in instances where all co-products, including CDR products, have a measurable energy content*[84]

[78] Puro Biochar Protocol, section 8.
[79] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.3 Leakage Emissions
[80] Climate Action Reserve, US and Canada Biochar Protocol, section 5.3
[81] Climate Action Reserve, US and Canada Biochar Protocol, section 5.3
[82] Isometric Biochar Production and Storage, section 7.1.1
[83] Isometric GHG Accounting Module section 6.1
[84] Isometric Biochar Production and Storage, section 7.1.1

Puro	Other high value products from the process can have emissions attributed through energy allocation. If not deemed high value, all emissions can be attributed to the biochar. Waste inputs can be excluded from the accounting.[85]
Verra	No co-product allocation for other products.
CAR	For biochar produced alongside other coproducts, an adjustment factor is used, weighing the energy content contained in the biochar over the total energy content in all products (for instance bio-oil).[86] All feedstock sourcing emissions must be accounted for purposely grown biomass (fuels + fertilizer). No emissions allocated for waste biomass feedstock.[87]
CSI	Avoided emissions from biomass feedstock burning can be credited for other fugitive emissions from the system, only if it's proven this was the management practice in the area. Avoided emissions from biomass left to decompose may be credited for other fugitive emissions on a case-by-case basis, where it is reasonably proven biochar is an incentive to avoid uncontrolled biomass decomposition. Fugitive emissions from the system can also be compensated by growing additional biomass (in which case the methane compensation effect needs to be calculated for each specific plant for the first 20 years). Additionally, the fugitive emissions can be compensated with the SPC fraction of the biochar.[88]

Table A1-21. BiCRS net removal calculations

Protocol	Scope
Isometric	The gross storage adjusted by a permanence factor[89], minus the counterfactual, minus all project emissions (including leakage).[90]
Puro	The gross CO_2 stored, minus the baseline, minus project emissions, minus leakage emissions.[91]
Verra	The gross CO_2 stored, plus avoided emissions at the sourcing stage (considered 0), minus all project emissions, minus all leakage emissions.[92]
CAR	The gross CO_2 stored multiplied by a permanence adjustment factor, minus all project emissions, minus leakage emissions, minus the baseline (assumed to be 0).[93]
CSI	The net carbon removed is the gross equivalent removed, minus the methane emissions factor from operating the process, minus the CO_2e factor from upstream processes, minus additional transportation emissions for distances

[85] Puro Biochar Methodology, section 7.1.15
[86] Climate Action Reserve, US and Canada Biochar Protocol, equation 5.3
[87] Climate Action Reserve, Eligible Biochar Feedstocks List
[88] Standard for Carbon Sink Certification for artisan Biochar production, section 14.6 and 14.7
[89]Isometric Biochar Storage in Agricultural Soils: https://registry.isometric.com/module/biochar-storage-agricultural-soils/1.1
[90] Isometric Biochar Production and Storage Protocol: section 8 Net CDR Calculation https://registry.isometric.com/protocol/biochar/1.0/ctn_1J1WFNQSE1S0QPD1#calculation-approach-and-reporting-period
[91] Puro Biochar Methodology, section 5.1
[92] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.5
[93] Climate Action Reserve, US and Canada Biochar Protocol, section 5.2.2

Protocol	Scope
	greater than 100km, plus any avoided emissions from decomposition/burning, plus the SPC fraction which can be used to compensate fugitive emissions.

Table A1-22. BiCRS feedstock eligibility

Protocol	**Feedstock Eligibility**
Isometric	Feedstock must be eligible by avoiding both direct and indirect leakage: Direct leakage refers to when payments to a supplier directly affect behavior in a way that increases GHG emissions. Indirect refers to when biomass procurement affects market price, leading to land use change or other market shifts. Project proponent must minimize both forms of leakage, based on the criteria below Market Leakage Eligibility (Both direct and indirect): *1. Project proponent does not pay for feedstock used* *2. Project proponent is paid a tipping fee to remove feedstock* *3. Project proponent paid for feedstock, but amount paid is lower than cost of harvesting + collection + transport + replacement of feedstock* 4. Same criteria as 3 but through a third party Eligibility (only indirect): *1. Feedstock is forest residue* *2. Feedstock is agricultural waste or animal waste* *3. Feedstock is non-marketable waste from an industrial production process* Eligibility (only direct): *1. Applicable to forest residues or downstream wood wastes only: Biomass originates from a regulated forest management project.* *2.Applicable to forest residues or downstream wood wastes only: Forest biomass results from forest management activities*[3] *in historically stable or increasing forest carbon stocks.* *3. Applicable to forest residues or downstream wood wastes only: Forest biomass resulting from forest management activities where Sourcing Area carbon stocks may be decreasing, but the forest management activity had to be carried out regardless.* *4. Applicable to agricultural crop residues only: The purchase contract signed between a Project Proponent and a feedstock supplier commits the Project Proponent to not purchase feedstock from a given acreage in consecutive years. Alternatively, feedstock may be sourced from the same acreage in sequential years if evidence is presented that the acreage has been monocropped (no crop rotation) for at least 5 years.* *5. Applicable to animal waste feedstocks only: Project Proponent paid a positive amount for their feedstock, but are able to demonstrate there is a surplus of feedstock available in the region.* To be eligible, feedstock to meet 1 of the first criteria or a combination of 1 and 1 criteria from lists two and three

Protocol	Feedstock Eligibility
	Recommended sourcing principles: - Historical land use - Tillage practices - Sustainable feedstock harvest[94]
Puro	Eligible feedstock must be: 1. Sustainably sourced or waste biomass, including agricultural waste, timber that has been damaged and use of invasive species. It can include MSW, food waste, green waste, animal waste, sludge and biosolids, pulp and paper sludge, agricultural crop waste and landscape conservation management. 2. Dedicated crops are allowed in marginal, degraded or contaminated land or *agricultural land that has been repeatedly cultivated for bioenergy crops (e.g. corn) for more than 20 years prior to the start of the CDR activity.*[95]
Verra	Waste biomass and not dedicated crops for CDR. Feedstock would have been left to decay or would have been combusted, with no possibility for energy recovery. If agricultural waste is used, *feedstock removal is limited to no more than 50 percent of total residues to protect against soil degradation*. Sourcing must not lead to increased agricultural activity or decline in carbon stocks (indirect market leakage). If food waste is used, production must not increase because of CDR (indirect leakage). Wood feedstocks must be from forest management activities and not lead to deforestation. Recycling waste is eligible if they comply with thresholds for heavy metal content. Up to 5% of facility input can be high carbon fly ash. Mineral additives to the feedstock are permitted for up to 10 wt%.[96]
CAR	Biomass that is a waste stream, byproduct or residue from forest agricultural and other resource management industries is eligible. Feedstock may be urban waste and food waste. Purposely grown crops are eligible under certain conditions. They may be diverted from bioenergy production, but it cannot represent more than 5% of energy production. If purpose grown, feedstocks must come from marginal lands (Capability Class 5 or 6 delineated by US Department of Agriculture), or reclaimed mining sites. Grown under conditions that cause no ecosystem carbon loss or direct land impacts.[97]
CSI	Eligible feedstock is that which originated from the artisan's farm, including cocoa byproducts, coffee peeling, rice thrashing, sawmills among others. May also be disaster debris and waste from maintenance of fields. Forest residue is allowed as well as food waste and agroforestry waste. Invasive species may be used with a plant to demonstrate the restoration of the organic carbon stored in them. Biomass may be purposely grown for bamboo and switch grass plantations. However, this excludes forest wood. [98]

[94] Isometric Biomass Feedstock Accounting Module, section 7.1.1
[95] Puro Biomass Sourcing Criteria: https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro_Biomass_Sourcing_Criteria.pdf
[96] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 4
[97] Climate Action Reserve, Eligible Biochar Feedstocks List
[98] Standard for Carbon Sink Certification for artisan Biochar production, section 6

Table A1-23. BiCRS baseline definitions

Protocol	Definition
Isometric	Baseline assumes no activities for the bio-oil/biochar project take place and no infrastructure is built.[99]
Puro	Baseline must be established depending on type of facility: new, retrofit or charcoal repurpose. The baseline would be the amount of char previously produced.[100]
Verra	*In the absence of the project activity, waste biomass is either left to decay or combusted for purposes other than energy production*. The baseline is set to 0 because the alternative fate could be decomposition.[101]
CAR	The baselines are the combustion or natural decomposition of the biomass feedstock. They are assumed to be 0 (as neither of these scenarios happens).[102]
CSI	The baseline is considered burning or uncontrolled decomposition of feedstock, which can be credited to offset other emissions in the process.[103]

Table A1-24. BiCRS storage durability, permanence, and timing of carbon removals

Protocol	Definition
Isometric	Depending on the quantification method, it can result in credits of 200- or 1000-year durability.[104] Mass of organic carbon stored must be adjusted by a *fraction of durable biochar that remains in the soil for the full duration of the crediting timeline*[105]
Puro	Permanence of over 200 years.[106]
Verra	Over a 100-year time horizon. Permanence factor for this time horizon determined based on pyrolysis temperature.[107]
CAR	Permanence in a 100-year timeline. Persistence to be proven by molar ratio of hydrogen/organic carbon of less than 0.7 in line with international biochar Initiative Guidelines.[108]

[99] Isometric Biochar Production and Storage, section 7.2
[100] Puro Biochar Protocol, section 6.3
[101] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 4
[102] Climate Action Reserve, US and Canada Biochar Protocol, section 5.1
[103] Standard for Carbon Sink Certification for artisan Biochar production, section 3
[104] Isometric Biochar Storage in Agricultural Soils Module, section 4:
https://registry.isometric.com/module/biochar-storage-agricultural-soils/1.0#quantification-of-coe
[105]Isometric Biochar Storage in Agricultural Soils:
https://registry.isometric.com/module/biochar-storage-agricultural-soils/1.1
[106] Puro Biochar Methodology, section 6
[107] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 8.2.2.1
[108] Climate Action Reserve, US and Canada Biochar Protocol, section 3.5

CSI	CO_2e of biochar with persistence greater than 1000 years. Determined based on the H/C ratio and assumed 75% of the carbon is Persistent Aromatic Carbon (PAC). The remaining carbon is assumed to be soil organic carbon with a mean residence time of 50 years.[109]

Table A1-25. BiCRS additionality requirements (see Glossary for definitions of each additionality type)

Protocol	Additionality Requirement(s)
Isometric	Financial, Regulatory, Market adoption and Environmental.
Puro	Regulatory and Financial.
Verra	Regulatory and Financial. [110]
CAR	Financial, Regulatory, and Environmental[111]
CSI	Financial [112]

4. Bioenergy with Carbon Capture and Storage (BECCS) Protocols

Tables that do not include a column for data source requirements indicate that the protocols did not specify any recommended or required data sources.

Note: Text in italics are directly taken from the standards/protocols. Footnotes indicate the specific section for each component in the respective protocol.

Table A1-26. BECCS project siting and construction emissions

Protocol	Scope	Data source requirement
Isometric	Equipment and materials manufacture, including all embodied emissions. Construction site emissions, including buildings, infrastructures, and land use change. Emissions associated with feasibility studies. [113] Account for all equipment[114]. *Use cradle-to-grave emission factors.*	None specified
Verra	Direct land use change caused by site disturbance/clearing. Emissions associated with erecting the CO_2 capture facility as well as any co-located units for CO_2 conditioning prior to transport (e.g.: compressor). Emissions from erecting the bioenergy facility are	*Process-based LCA may be conducted with material LCI data from NETL, GREET, Federal LCA Commons Alternatively, estimating data based on purchasing may*

[109] Standard for Carbon Sink Certification for artisan Biochar production, section 12
[110] VM0044 Biochar Utilization in Soil and Non-Soil Application, section 7
[111] Climate Action Reserve, US and Canada Biochar Protocol, Section 3.4
[112] Standard for Carbon Sink Certification for artisan Biochar production, section 18
[113] Isometric Biogenic Carbon Capture and Storage, section 7.2 table 1
[114] Isometric Embodied Emissions Accounting, section 2.0: system boundaries: https://registry.isometric.com/module/embodied-emissions/1.0#system-boundaries

	excluded (only dedicated CO_2 units are accounted for)[115]. Include embodied emissions from BECCS facility only; embodied emissions from bioenergy facilities are excluded.[116]	*leverage the US EEIO approach. GREET and NETL have land use change/conversion factors.* [117]
Gold Standard	Emissions associated with the erection of the plant, as well as transportation and storage facilities, including any land use change emissions and soil organic carbon loss in land used for project[118]. Embodied emissions of materials used for construction of capture and storage facilities are **excluded**[119].	*Life-cycle methods in accordance with host country or jurisdictional standards or, if unavailable, international standards (e.g. ISO, IEC)* [120].GREET, IPCC Guidelines or a National source for land use change[121]

Table A1-27. BECCS transportation emissions

Protocol	Scope	Data source requirement
Isometric	Transport of biomass feedstock and transport of compressed or liquid CO_2[122] . *Include all emissions associated with the fuel-cycle such as direct combustion of fuel as well as indirect upstream emissions, including production and distribution of fuel or electricity.* *Embodied life cycle emission factors must be used for vehicles and infrastructure produced, constructed, and utilized for the CO_2 removal project, and this must be calculated in addition to the Energy Usage or Distance-Based Methods.*[123]	Can be calculated using energy usage or distance-based methods.[124]
Verra	Emissions associated with transporting the biomass feedstock to the facility, as well transporting capture materials.[125]	*Default emission factor to transport biomass cargo by different modes (ship, truck, or rail), using CO2 transport emission factors as a proxy (DEFr from Section 6 of VMD0057) (g CO2/t-km)*[126]

[115] VMD 0059 CO_2 Capture from Bioenergy, section 5.1, figure 1
[116] VMD 0059 CO_2 Capture from Bioenergy, section 5.2, Appendix 2, table 2
[117] VMD 0059 CO_2 Capture from Bioenergy, section 5.2, Appendix 2, table 2
[118] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P3 and P4 and section 5.2.3
[119] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P2
[120] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P4 and section 5.11
[121] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, 5.11
[122] Isometric Biogenic Carbon Capture and Storage, section 7.6.3.6
[123] Isometric Transportation Emissions Accounting Module
[124] Isometric Transportation Emissions Accounting Module
[125] VMD 0059 CO_2 Capture from Bioenergy, section 5 and section 5.4.3
[126] VMD 0059 CO_2 Capture from Bioenergy, section 5.4.3.4

Gold Standard	Transporting biomass and biomass residues to the facility and transporting all consumables and ancillary equipment into the facility[127].	Use values from CDM TOOL12 for transportation of freight

Table A1-28. BECCS energy (electricity and fuel) use emissions

Protocol	Scope	Data source requirement	Miscellaneous
Isometric	*The emissions associated with energy use must account for all operations that consume energy within the CDR project processes, through the usage of both electricity and fuel.* Electricity emission factors represent the life cycle of the fuel used to generate electricity and of the generator. [128]	If project is grid powered, use *DOE National Transmission Needs Study* emission factor for grid electricity. No specific emission factor source is required for projects with PPA, but factors must include generator and fuel. [129]	Differentiates accounting for facilities consuming under (non-intensive) and over 200 GWh (intensive). Annual volumetric matching for non-intensive facilities, hourly volumetric for intensive. Waste heat can be used as a burden free energy input.[130]
Verra	Emissions for all electricity and fuels consumed, including upstream emissions from generation. Account for grid electricity separately to dedicated electricity and heat generation. Waste heat can be used, carrying a burden of 0 emissions.[131]	An emission factor for the emission of each GHG (CO_2, CH_4, N_2O) for each fuel type.[132] Electricity emission factors outlined in VT0011 Electricity System Emission Factors.	
Gold Standard	Account for electricity and fuel use both onsite and offsite[133].	GREET, a national inventory, or another equivalent life-cycle method. For fuel use, calculate emissions with a well-to-tank or well-to-meter factor[134].	

[127] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P1,P2 and P4
[128] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[129] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[130] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[131] VT0010 Emissions from Electricity Consumption and Generation.
[132] VMD 0059 CO_2 Capture from Bioenergy, section 5.3.1
[133] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P7 and P8.
[134] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3 P6

Table A1-29. BECCS operation and direct emissions.

Protocol	Scope	Data source requirement
Isometric	Biomass feedstock sourcing, use of consumables including embodied emissions. Waste processing and disposal. Surveys and emissions associated with sampling for MMRV. Maintenance of project site including refurbishments and replacement. [135] Other scope 3 emissions such as staff travel.	
Verra	Ongoing emissions associated with the supply of consumables such as chemicals and water. Other emissions associated with maintenance and operation. To include upstream emissions of biomass consumed and upstream emissions of capture materials. Emissions from cultivating and processing biomass needs to be accounted for. Include methane emission for *fugitive and venting emissions from on-site fuel use*[136]	*Highly dependent on the chemical – some data are available from NETL, GREET, and US LCI Alternatively, estimating data based on purchasing may leverage the US EEIO approach*[137].
Gold Standard	Emissions from sourcing biomass, including all processing. Emissions from the fermentation process, including any venting. Emissions from the capture process, compression, transportation and injection. Embodied emissions of consumables need to be included, such as emissions from sorbent production. Emissions associated with transporting CO_2 from capture to injection site. Fugitive emissions at injection sites need to be quantified, as well as emissions from the subsurface to the atmosphere. All emissions resulting from land management, depending on whether it's grassland or cropland. All emissions associated with soil fertilization and amendment as well as emissions from seeding and harvesting the feedstock[138].	

Table A1-30. BECCS end-of-life emissions

Protocol	Scope

[135] Isometric Biogenic Carbon Capture and Storage, section 7.2 table 1
[136] VMD 0059 CO_2 Capture from Bioenergy, section 5, table 1
[137] VMD 0059 CO_2 Capture from Bioenergy, section 5.2, Appendix 2, table 2
[138] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, table 3.

Isometric	End of life of the project facility and emissions associated with ongoing MMRV sampling activities. [139]
Verra	Emissions associated with deconstruction, waste disposal and materials recycling[140].
Gold Standard	Emissions associated with decommissioning of facilities are excluded [141].

Table A1-31. BECCS counterfactuals

Protocol	Scope	Approach
Isometric	Counterfactual Storage: CO_2 that would have been permanently stored in the biomass in the absence of the CDR project. Known as ineligible biomass. Biomass, whose counterfactual fate is being released in the next 15 years is eligible biomass. [142]	*If the counterfactual fate of the biomass includes the stored biogenic C being emitted as GHGs with a GWP100>1, the total biomass eligible is equal to the minimum of:* *(1) the CO_2e (evaluated at GWP100) of counterfactually released GHGs emitted within 15 years* *(2) the total stored CO_2 in the biomass minus the CO_2 in biomass that would not have counterfactually been released within 50 years.* *Landfilled wood is not an eligible feedstock, unless the Project Proponent can demonstrate the counterfactual fate would release all stored biogenic carbon within 15 years.* *Feedstocks that are sourced through government managed or funded wildfire mitigation or restoration activities will be assigned a counterfactual storage value of 0.* Applicable to non-forestry feedstocks: *The biomass feedstock was not grown for the purposes of energy production and does not have a likely counterfactual energy production use.* [143]

[139] Isometric Biogenic Carbon Capture and Storage, section 7.6.3.3
[140] VMD 0059 CO_2 Capture from Bioenergy, section 5.2, Appendix 2, table 2
[141] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, P18
[142] Isometric Biomass Feedstock Accounting Module, section 2.2 Table 5
[143] Isometric Biomass Feedstock Accounting Module, section 2.2 Table 5 and Table 6.

Verra	No counterfactual storage considered.[144]	Not applicable.
Gold Standard	No counterfactual storage considered.	Not applicable.

Table A1-32. BECCS economic leakage (market-mediated impacts)

Protocol	Scope	Approach
Isometric	For biomass projects, replacement emissions (to compensate for biomass that was serving another purpose) are the minimum leakage. Projects that would lead to ecological leakage associated with land use change are ineligible.[145]	Replacement emissions: The addition of replacement emissions associated with energy, embodiment and transportation of new feedstock serving a market need that the CDR project could be displacing. Cases where replacement emissions are exempt are the following: *If the feedstock currently serves no purpose, such as mill residues in a stockpile or forest residues sitting on the forest floor, there are deemed to be no replacement emissions.* *For project feedstock usage above the percentage of what is theoretically possible to use for a given purpose (the 'Sustainable Use Rate') the feedstock would be considered true waste and therefore not require calculation of replacement emissions.* For environmental services replacement emissions, the mass of replacement can be used to calculate the emissions. For example, the fertilizer capacity from feedstock that needs to be replaced can be calculated by sampling the amount of nitrogen, phosphorus and potassium in each batch. The counterfactual scenario must account for replacing the same amount of NPK.[146]
Verra	Leakage from increased harvesting of biomass needs to be accounted for. If biomass is eligible under criteria, market leakage is 0. For ineligible biomass, market leakage needs to be accounted for based on the mass diverted from an alternative use.[147]	*Use an embodied emissions factor, determined through a life cycle assessment (LCA), in Equation (10) to calculate leakage emissions from cultivation.* Otherwise, use total area to harvest additional feedstock and values provided in CDM TOOL16 to calculate leakage from cultivation. For market leakage, assume the most likely

[144] VMD 0059 CO_2 Capture from Bioenergy, section 5.4
[145] Isometric Biomass Feedstock Accounting Module, section 3.2
[146] Isometric Biomass Feedstock Accounting Module, section 3.2
[147] VMD 0059 CO_2 Capture from Bioenergy, section 5.4.3.2 and 5.4.3.3

Protocol	Scope	Approach
		alternative scenario for biomass and use values in CDM TOOL16. [148]
Gold Standard	Leakage emissions from diverting biomass from other activities, as well as diverting other economic activities to purposefully grow biomass. No leakage is considered if land was abandoned or had the same level of other economic activity (e.g.: cattle) and no settlements were displaced from the area within the project boundary. For dedicated biomass: if the project is considered large scale, no activity shifting is allowed. If the project is considered small scale, leakage is considered 0 if shifting is under 10%. If leakage is higher than 10% and smaller than 50%, a value of 15% of the difference between baseline emissions and project emissions is used. For biomass residues: no leakage considered if residues are dumped to decay in a field, dumped in a landfill, or the waste is burned in an uncontrolled manner. If waste biomass was used for energy production, other applications or its end use cannot be determined, leakage must be established. Leakage is calculated using the energy value of the waste feedstock and assuming all this energy needs to be replaced with the most carbon intensive fossil fuel. If the facility shows to have increased the quantity of biomass produced in the region, compared to a previous 3 year average, leakage due to increased production needs to be accounted for[149]. Loss of soil organic carbon due to the diversion of the feedstock needs to be accounted for, depending on climate region and soil type, only if distributed area is over 10% of the soil stratum[150].	Leakage due to increase in production needs to be accounted for using a suitable method which is ISO14044 compliant for the mass of increased biomass consumed. Use values provided by CDM TOOL16[151].

[148] VMD 0059 CO_2 Capture from Bioenergy, section 5.4.3.2 and 5.4.3.3
[149] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.7 and Appendix 1
[150] CDM TOOL16 Project and Leakage Emissions from Biomass, section 5.1.1
[151] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.7

Table A1-33. BECCS multifunctionality

Protocol	Scope
Isometric	*In cases where the project has demonstrated that the co-product facility is non-additional, universal equipment may be excluded from the system boundary.*[152] Emissions avoided by the BECCS project, such as providing a secondary source of low carbon electricity, avoiding landfill emissions and reducing waste transport emissions **are not credited.** [153] In terms of co-product allocation, in the most conservative approach, CDR products will take full burden. Where processes are physically separable, processes that do not contribute to CDR can be excluded from the boundary.Where processes are not physically separable, the substitution method may be used to account for avoided emissions associated with the production of a co-product, only if these emissions are deemed *residual* or *hard-to-abate.* If co-product leads to CDR credit, allocation should be done based on carbon mass balance.[154]
Verra	Emissions from the bioenergy facility alone are excluded from the project boundary.
Gold Standard	The CO_2 stream is classified into project and non-project streams. The project stream contains CO_2 from fermented biomass from a renewable feedstock. Non-project streams would be CO_2 capture from fermented biomass from ineligible sources and CO_2 captured from post-combustion.[155]

Table A60 BECCS net removal calculation

Protocol	Calculation
Isometric	Gross removal, minus counterfactual, minus all project emissions.[156]
Verra	Net CO_2 transported to storage, minus all project emissions, minus any leakage.[157]
Gold Standard	Net removed amount is project stream, minus all project emissions, minus leakage, minus baseline.[158]

Table B61 BECCS feedstock eligibility requirements

Protocol	Feedstock Eligibility
Isometric	Feedstock must be eligible by avoiding both direct and indirect leakage: Direct leakage refers to when payments to a supplier directly affects behavior in a way that increases GHG emissions. Indirect refers to when biomass procurement affects market price, leading to land use change or other market

[152] Isometric Biogenic Carbon Capture and Storage, section 7.3.1
[153] Isometric Biogenic Carbon Capture and Storage, section 7.3.3
[154] Isometric GHG Accounting Module section 6.1
[155] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.6.2
[156] Isometric Biogenic Carbon Capture and Storage, section 7.6
[157] VMD 0059 CO_2 Capture from Bioenergy section 5.1
[158] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.8

Protocol	Feedstock Eligibility
	shifts. Project proponent must minimize both forms of leakage, based on the criteria below Market Leakage Eligibility (Both direct and indirect): *1. Project proponent does not pay for feedstock used* *2. Project proponent is paid a tipping fee to remove feedstock* *3. Project proponent paid for feedstock, but amount paid is lower than cost of harvesting + collection + transport + replacement of feedstock* 4. Same criteria as 3 but through a third party Eligibility (only indirect): *1. Feedstock is forest residue* *2. Feedstock is agricultural waste or animal waste* *3. Feedstock is non-marketable waste from an industrial production process* Eligibility (only direct): *1. <u>Applicable to forest residues or downstream wood wastes only:</u> Biomass originates from a regulated forest management project.* *2.<u>Applicable to forest residues or downstream wood wastes only:</u> Forest biomass results from forest management activities in historically stable or increasing forest carbon stocks.* *3. <u>Applicable to forest residues or downstream wood wastes only:</u> Forest biomass resulting from forest management activities where Sourcing Area carbon stocks may be decreasing, but the forest management activity had to be carried out regardless.* *<u>4. Applicable to agricultural crop residues only:</u> The purchase contract signed between a Project Proponent and a feedstock supplier commits the Project Proponent to not purchase feedstock from a given acreage in consecutive years. Alternatively, feedstock may be sourced from the same acreage in sequential years if evidence is presented that the acreage has been monocropped (no crop rotation) for at least 5 years.* *<u>5. Applicable to animal waste feedstocks only:</u> Project Proponent paid a positive amount for their feedstock, but are able to demonstrate there is a surplus of feedstock available in the region.* To be eligible, feedstock to meet 1 of the first criteria or a combination of 1 and 1 criteria from lists two and three Recommended sourcing principles: - Historical land use - Tillage practices - Sustainable feedstock harvest[159]
Verra	Eligible biomass is waste biomass, including primary or secondary processing, food waste, sludge, manure, bagasse, MSW, tertiary wood waste, lignin, invasive species management waste, park management activities and wildfire management activities. Feedstock may be forestry wastes and may be a dedicated crop if grown under a regulatory program or under a sustainability certification. *The biomass must not be produced from a converted ecosystem*

[159] Isometric Biomass Feedstock Accounting Module, section 7.1.1

Protocol	Feedstock Eligibility
	such as where forest or wetland has been converted to agriculture/cropland 10 years or more before the start of the project[160].
Gold Standard	Demonstrated renewable biomass. Renewable biomass can be: • Purposely grown crops from forests, woody biomass or non-woody biomass, if the management practices put in place, ensure that the level of carbon stocks does not decrease in activity area. • Waste biomass, where disposing of the waste does not affect the area's carbon pools. • Non-fossil fraction of industrial or municipal solid waste. • The land where biomass is cultivated cannot contain wetlands or be subjected to flood irrigation or be organic soil (10 cm or more of thickness and 20% by organic carbon weight or a lower percentage for soils subject to water saturation that contain clay). • For waste biomass, the proponent must demonstrate supply is currently at least 25% larger than current demand feedstock in the region.[161]

Table A62 BECCS baseline definitions

Protocol	Baseline definition
Isometric	*New-build: The baseline scenario assumes that all activities associated with the Bio-CCS Project and the wider facility do not take place and no associated infrastructure is built.* *Retrofit: The baseline scenario assumes that the activities associated with the Bio-CCS component of the wider facility do not take place and no additional infrastructure associated with CCS is built.*[162]
Verra	The baseline is the bioenergy project in the absence of a CO_2 capture process. Or, if an existing capture unit is in place, the baseline is the current capture capacity (compared to an expanded extension).[163]
Gold Standard	Alternative scenarios need to be defined by project proponent. The scenario with the least emissions is considered the baseline[164].

Table A63 BECCS storage durability, permanence, and timing of carbon removals.

Protocol	Durability requirements
Isometric	>1000 years[165]
Verra	Not defined

[160] VMD 0059 CO_2 Capture from Bioenergy Appendix 1.
[161] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, Appendix 1
[162] Isometric Biogenic Carbon Capture and Storage, section 7.4
[163] VMD 0059 CO_2 Capture from Bioenergy, section 5.2
[164] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.5
[165] Isometric Biogenic Carbon Capture and Storage, Summary

Gold Standard	Not defined

Table A64 BECCS additionality requirements

Protocol	Additionality requirements
Isometric	Financial, Regulatory, Market Adoption and Environmental. [166]
Verra	Regulatory and Financial. [167]
Gold Standard	Regulatory and Financial[168]

5. Land-Based Mineralization Protocols

The protocols reviewed under mineralization cover a broad range of technologies including ex-situ mineralization in quarries and industrial sites (Isometric), carbonated materials (Puro), CO_2 utilization in concrete (Verra) and carbonation of reactive mineral wastes (Gold Standard). This diversity reflects the wide technological landscape for mineralization and the challenge of creating harmonized accounting for different system configurations.

Tables that do not include a column for data source requirements indicate that the protocols did not specify any recommended or required data sources.

Note: Text in italics are directly taken from the standards/protocols. Footnotes indicate the specific section for each component in the respective protocol.

Table A1-34. Mineralization project siting and construction emissions

Protocol	Scope	Data source requirement
Isometric (ex-situ mineralization in quarries and industrial sites)	Project establishment emissions from the *point of project inception through after the operations have taken place.*[169] Emissions associated with: Equipment and materials transport to site. Construction and installation. Initial surveys and feasibility studies. Raw materials and equipment used in the fabrication, assembly and construction of machinery utilized for	None specified

[166] Isometric Biogenic Carbon Capture and Storage, section 6.4
[167] VMD 0059 CO_2 Capture from Bioenergy, section 5.2
[168] Gold Standard, Biomass Fermentation with Carbon Capture and Geologic Storage, section 5.3
[169] Isometric Open System Ex situ Mineralization Protocol, section 10.5.4

Protocol	Scope	Data source requirement
	spreading, tilling, churning, feedstock manipulation and sampling. *Use cradle-to-grave emission factors*[170] for all equipment. Include *land use change as a result of project establishment*[171]	
Puro (carbonated materials)	Cradle-to-gate emissions of: Erecting the carbonation facility. System boundaries include emissions from production and supply of all materials.[172] *Follow the ISO 14040 standard*.	None specified
Verra (CO_2 utilization in concrete)	Embodied emissions for equipment, facilities, and infrastructure in: The CO_2 source plant (for example the DAC plant). The cement production plant. The concrete production plant where cement is reacted with CO_2.[173]	None specified
Gold Standard (carbonation of reactive mineral wastes)	Embodied emissions for: Additional processing of mineral waste. Constructing new infrastructure.[174]	Use facility lifetime of 20 years for infrastructure establishment and embodied emissions. *Default factors for Neustark carbonation plants over a facility lifetime of 20 years are given in Section 5.7.(h), Parameter ID 11.*[175]

Table A1-35. Mineralization transportation emissions

Protocol	Scope	Data source requirement
Isometric (ex-situ mineralization in quarries and industrial sites)	*Transportation of:* *Feedstock to the Project location (where applicable). Rock from quarry to crushing site.*	None specified

[170] Isometric Embodied Emissions Accounting Module
[171] Isometric Open System Ex situ Mineralization Protocol, section 10.2
[172] Puro Carbonate materials Methodology, section 4.03
[173] VM0043 CO_2 Utilization in Concrete Production section 5
[174] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.7 c
[175] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.7 c

Protocol	Scope	Data source requirement
	Transportation and shipping related to collecting samples for environmental monitoring.[176] *Include all emissions associated with the fuel-cycle such as direct combustion of fuel as well as indirect upstream emissions, including production and distribution of fuel or electricity.* *Embodied life cycle emission factors must be used for vehicles and infrastructure produced, constructed, and utilized for the CO_2 removal project, and this must be calculated in addition to the Energy Usage or Distance-Based Methods.*[177,178]	
Puro (carbonated materials)	Transportation of: Raw materials from their point of production to the plant. *The system boundary excludes the distribution of the material, the use phase and the end-of-life of the material.*[179]	None specified
Verra (CO_2 utilization in concrete)	Transportation of: CO_2 to the facility. Cement to the facility. Produced concrete to the end user.	Emissions factor provided per tonne-mile for different transport modes[180]
Gold Standard (carbonation of reactive mineral wastes)	Transportation of: CO_2 to the carbonation plant. Emissions for transporting the mineral feedstock, as well as mobile equipment and consumables to the plant must be included only if they *are deemed significant*. If no additional transportation of mineral feedstock is required relative to the baseline, mineral feedstock transportation emissions are set to 0.[181]	Use values for freight or transport from CDM Tool 12 or Gold standard Tool 02

[176] Isometric Open System Ex situ Mineralization Protocol, section 10.6.2
[177] Isometric Transportation Emissions Accounting Module
[178] Isometric Transportation Emissions Accounting Module
[179] Puro Carbonate materials Methodology, section 4.06
[180] VM0043 CO_2 Utilization in Concrete Production section 8.2.4, Table 3
[181] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.7 b

Table A1-36. Mineralization energy (electricity and fuel) use emissions

Protocol	Scope	Data source requirements	Miscellaneous
Isometric (ex-situ mineralization in quarries and industrial sites)	*The emissions associated with energy use must account for all operations that consume energy within the CDR project processes, through the usage of both electricity and fuel*. Electricity emission factors represent the life cycle of the fuel used to generate electricity and of the generator.[182]	If the project is grid powered, use *DOE National Transmission Needs Study* emission factor for grid electricity. No specific emission factor source is required for projects with PPA, but factors must include generation and fuel.[183]	Different accounting methods are required for *non-intensive* facilities consuming less than 200 GWh annually, which can use annual volumetric matching, and *intensive* facilities consuming more than 200 GWh annually, which must use hourly volumetric matching. Waste heat can be used as a burden free energy input.[184]
Puro (carbonated materials)	Energy inputs for all processes involved, including manufacturing, use and disposal[185]. Must use an emission factor that accounts for the whole generation life cycle.	None specified	
Verra (CO_2 utilization in concrete)	All electricity and fuel used for CO_2 sourcing, including capture, compression, and transport. For cement and concrete production, only account for incremental electricity and fuel used relative to the baseline activity (manufacturing precast concrete).[186,187]	*Use a grid emission factor published by a government agency.* *Where grid emission factors are not available from a government agency, an emission factor published by another reputable and recognized source, and reviewed for publication by an appropriate qualified, independent organization or appropriate peer review group may be used.*[188]	
Gold Standard (carbonation of reactive mineral wastes)	Account for energy and fuel use both onsite and offsite.[189]	A grid emission factor published by a government or national agency. Alternatively, use CDM Tool 07 to calculate	

[182] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[183] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[184] Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
[185] Puro Carbonate materials Methodology, section 5.3
[186] CDM Tool 7: To calculate the emission factor for an electricity system.
[187] CDM Tool 5: Baseline, Project and or leakage emissions from electricity consumption and monitoring of electricity generation: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v3.0.pdf
[188] VM0043 CO_2 Utilization in Concrete Production section 8.2.2
[189] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.7.3

Protocol	Scope	Data source requirements	Miscellaneous
		emissions for grid electricity.[190] For fuel, use emission factors from the commercial supplier. Alternatively, use chemical composition method or net calorific value method to calculate emission factors.[191]	

Table A1-37. Mineralization operational and direct emissions

Protocol	Scope
Isometric (ex-situ mineralization in quarries and industrial sites)	Direct emissions from quarrying, crushing and grinding, sampling and analysis. Direct emissions from other miscellaneous activities such as staff transport. *Life cycle emissions of consumables and water.*
Puro (carbonated materials)	Direct emissions from CO_2 and mineral feedstock sourcing and operating the carbonation process. *The system boundary excludes the distribution of the material, the use phase and the end-of-life of the material.*[192]
Verra (CO_2 utilization in concrete)	Direct emissions from producing the cement, including calcination, from the CO_2 capture process, and from operating the concrete production process.[193] CO_2 supplied that is lost and not mineralized must be considered a project emission.
Gold Standard (carbonation of reactive mineral wastes)	Direct emissions from CO_2 capture and processing, liquefaction, refrigeration, and the operation of the carbonation process. Must include any CO_2 evaporation and physical leakages.[194]

Table A1-38. Mineralization end-of-life emissions

Protocol	Scope
Isometric (ex-situ mineralization	*Anticipated emissions:* *closure of storage sites, including embodied emissions associated with equipment and materials manufacture, transport of equipment and materials to site and emissions associated with energy use and consumables use for*

[190] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.12 parameter 9
[191] Gold Standard Tool 01: Project or Leakage Emissions from Fossil Fuel Combustion.
[192] Puro Carbonate materials Methodology, section 4.06
[193] VM0043 CO_2 Utilization in Concrete Production section 5
[194] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.2 table 3

in quarries and industrial sites)	*closure operations including installation and groundworks, as well as waste processing activities and emissions associated with land use change.*[195]
Puro (carbonated materials)	The system boundary must include disposal of waste associated with all processes.[196]
Verra (CO_2 utilization in concrete)	Not mentioned.
Gold Standard (carbonation of reactive mineral wastes)	Emissions associated with decommissioning of facilities are excluded.[197]

Table A1-39. Mineralization counterfactuals

Protocol	Scope	Data Requirements	Miscellaneous
Isometric (ex-situ mineralization in quarries and industrial sites)	*Carbon removal which would have occurred in the absence of removal activities.*[198]	Counterfactual carbonation is quantified using samples collected from a subset of the project area. Geochemical models can be used to validate empirical measurements of feedstock.[199] To quantify the counterfactual, an adjusted version of the Steinour equation, which uses bulk elemental oxide composition to estimate the maximum CO_2 removal potential is used.	
Puro (carbonated materials)	*The amount of CO_2 that the feedstock material would have sequestered naturally (in the absence of project activities) in 50 years following the commencement of the accelerated carbonation activity.*[200]	Estimate based on mineralogy, physical form and likely storage conditions. Average sequestration rates may be used. [201]	*Projects, where the baseline sequestration amount is estimated to be 50 % or more of the total amount sequestered are not eligible to be credited under the Carbonated Materials methodology*.

[195] Isometric Open System Ex situ Mineralization Protocol, section 10.5.2, table 6
[196] Puro Carbonate materials Methodology, section 5.3.2
[197] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.2 table 3
[198] Isometric Open System Ex situ Mineralization Protocol, section 10.5.2
[199] Isometric Open System Ex situ Mineralization Protocol, section 10.5.2, table 6
[200] Puro Carbonate materials Methodology, section 5.4
[201] Puro Carbonate materials Methodology, section 5.4

Verra (CO_2 utilization in concrete)	The amount of CO_2 that would have naturally been stored in the concrete must be deducted as a penalty. Avoided emissions from reducing cement mass demand compared to the baseline are credited.[202]	Carbon content in cement of both the baseline and the project sample can be measured using a carbon analyzer and then subtracted to yield the additional CO_2 removals. Alternatively, a default value of 60% mineralization from the injected CO_2 can be used for both the baseline and the project samples.[203]	
Gold Standard (carbonation of reactive mineral wastes)	Natural removals due to carbonation need to be accounted for as a penalty if they represent >2% of project sink capacity. [204]	Natural carbonation to be determined by using material composition, morphology and expected environmental conditions such as temperature, precipitation and groundwater pH[205]	

Table A1-40. Mineralization economic leakage (market-mediated impacts)

Protocol	Scope
Isometric (ex-situ mineralization in quarries and industrial sites)	Include increases in GHG emissions associated with the Project shifting emissions or causing a knock-on effect that increases emissions elsewhere.[206] *This includes emissions associated with activity-shifting, market leakage and ecological leakage*.
Puro (carbonated materials)	Not mentioned.
Verra (CO_2 utilization in concrete)	Not mentioned.
Gold Standard (carbonation of reactive mineral wastes)	Leakage is 0 provided the feedstock has no baseline market or use. Market shift emissions associated with having to replace the mineral feedstock must be included if the feedstock has a baseline market or use. Additionally, leakage emissions may arise from an increase in biogenic CO_2 production if the feedstock is sourced from a new facility; these leakage emissions must be included. [207]

[202] VM0043 CO_2 Utilization in Concrete Production section 8.1.2
[203] VM0043 CO_2 Utilization in Concrete Production section 8.1.2
[204] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.5
[205] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.5
[206] Isometric Open System Ex situ Mineralization Protocol, section 10.5.7
[207] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.8

Table A1-41. Mineralization multifunctionality

Protocol	Requirements
Isometric (ex-situ mineralization in quarries and industrial sites)	In terms of co-product allocation, in the most conservative approach, CDR products will take full burden. Where processes are physically separable, processes that do not contribute to CDR can be excluded from the boundary.Where processes are not physically separable, the substitution method may be used to account for avoided emissions associated with the production of a co-product, only if these emissions are deemed *residual* or *hard-to-abate.* If co-product leads to CDR credit, allocation should be done based on carbon mass balance.[208] Waste inputs are treated as burden-free.
Puro (carbonated materials)	*An allocation of the production burdens can be made between the co-products[209]. The burdens from production of e.g. waste feedstock material can be excluded from the system boundary, but the supply and handling of the waste feedstock material must be included[210].*
Verra (CO_2 utilization in concrete)	Not specified.
Gold Standard (carbonation of reactive mineral wastes)	Not specified.

Table A1-42. Mineralization net removal calculation

Protocol	Scope	Data source requirement
Isometric (ex-situ mineralization in quarries and industrial sites)	The gross storage, minus the counterfactual, minus all project emissions (including leakage).[211]	
Puro (carbonated materials)	The amount of CO_2 stored, minus the emissions of the production process, minus the amount stored in the baseline (counterfactual).[212]	The stored amount is a product of the total amount of carbonated material times the amount of CO_2 reacted per kg of material,

[208] Isometric GHG Accounting Module section 6.1
[209] Puro Carbonate materials Methodology, section 4.05
[210] Puro Carbonate materials Methodology, section 4.04
[211] Isometric Open System Ex situ Mineralization Protocol, section 10.5
[212] Puro Carbonate materials Methodology, section 5.1 and 5.2

		determined via lab measurements.
Verra (CO_2 utilization in concrete)	The net-removed CO_2 is equal to the gross removals, minus a factor composed of: the gross removal divided by the gross removal, minus the project emissions, plus the counterfactual, all of this multiplied by the incremental electricity and fuel emissions compared to the project baseline, plus the emissions associated with the capture, transport and compression of CO_2, plus the reversals.[213]	
Gold Standard (carbonation of reactive mineral wastes)	Net removed amount is gross sinks, minus project emissions, minus leakage emissions, minus baseline (counterfactual) removals. [214]	Gross amount captured may be calculated via ex-ante quantification, through the mass of mineral feedstock and the sink factor per unit mass. Or it may be quantified via ex-post quantification, using the difference of mass of CO_2 in and out of the reactor. [215]

Table A1-43. Mineralization feedstock eligibility requirements

Standard	Feedstock Eligibility Requirements
Isometric (ex-situ mineralization in quarries and industrial sites)	No feedstock from carbonate sources is permitted. Feedstocks from mining waste can be used but might require further characterization to comply with local regulations. Homogeneity within a batch needs to be proved through characterization.[216]
Puro (carbonated materials)	Both waste and purpose-produced feedstock are permitted. [217].
Verra (CO_2 utilization in concrete)	*For removals, the project proponent must provide clear and transparent evidence that the source is a DAC or biogenic CO_2 facility.*[218] Other materials can be dedicated feedstocks for the manufacture of concrete.
Gold Standard (carbonation of reactive mineral wastes)	Only waste feedstock, proven to have no alternative use, before it enters a downstream process or it is landfilled. CO_2 sources from atmospheric removal or biogenic sources are eligible.[219]

[213] VM0043 CO_2 Utilization in Concrete Production section 8.4
[214] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.9
[215] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.6
[216] Isometric Rock and Mineral Characterization Module
[217] Puro Carbonate materials Methodology, section 4.04
[218] VM0043 CO_2 Utilization in Concrete Production section 8.4
[219] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 3.2.4 and 3.2.6

Table A1-44. Mineralization baseline definitions

Standard	Baselines
Isometric (ex-situ mineralization in quarries and industrial sites)	*Establishment of Baseline based on business-as-usual industrial practices occurs.* [220]
Puro (carbonated materials)	The counterfactual can be ignored in cases where natural sequestration would have been ≤1% of total amount sequestered. [221]
Verra (CO_2 utilization in concrete)	The baseline is pre-cast concrete made through traditional processes. [222]
Gold Standard (carbonation of reactive mineral wastes)	Alternative scenarios need to be defined by the project proponent. The scenario with the least emissions is considered the baseline. [223]

Table A1-45. Mineralization storage durability, permanence, and timing of carbon removals.

Standard	Durability and Permanence
Isometric (ex-situ mineralization in quarries and industrial sites)	1000+ years[224]
Puro (carbonated materials)	100 years[225].
Verra (CO_2 utilization in concrete)	Not addressed
Gold Standard (carbonation of reactive mineral wastes)	1000+ years. Carbonated products *shall not be subject to conditions that could impact its durability*. Should not be used for agricultural soils, clinker production, ceramics, or high temperature processes. If used as aggregate for building materials, resulting materials must fulfill standards. [226]

Table A1-46. Mineralization additionality requirements

Standard	Additionality requirements
Isometric (ex-situ mineralization in quarries and industrial sites)	Financial, Regulatory, Market Adoption and Environmental. [227]

[220] Isometric Open System Ex situ Mineralization Protocol, section 10.3
[221] Puro Carbonate materials Methodology, section 5.4.7
[222] VM0043 CO_2 Utilization in Concrete Production section 6
[223] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.4
[224] Isometric Open System Ex situ Mineralization Protocol, section 12.1
[225] Puro Carbonate materials Methodology, section 1
[226] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, summary
[227] Section 2.5.3 of the Isometric Standard

Puro (carbonated materials)	Regulatory and financial.
Verra (CO_2 utilization in concrete)	Regulatory and Financial. [228]
Gold Standard (carbonation of reactive mineral wastes)	Financial, Regulatory and Market Adoption. [229]

6. Enhanced Rock Weathering (ERW) protocols

Tables that do not include a column for data source requirements indicate that the protocols did not specify any recommended or required data sources.

Note: Text in italics are directly taken from the standards/protocols. Footnotes indicate the specific section for each component in the respective protocol.

Table A1-47. ERW project siting and construction emissions

Protocol	Scope
Isometric	Emissions associated with all quarrying activities; crushing and grinding, feedstock characterization and emissions for spreading at agricultural application site. Must include embodied emissions of all equipment[230].
Puro	Emissions associated with the establishment of terrestrial storage site; construction works, terracing, fencing, building, soil disturbance (land use change emissions)[231].

Table A1-48. ERW transportation emissions

Protocol	Scope	Data source requirement
Isometric	Emissions from transportation of feedstock to agricultural site; transportation of rock from quarry to crushing site; and transportation and shipping related to collecting samples for environmental monitoring[232]. *Include all emissions associated with the fuel-cycle such as direct combustion of fuel as well as indirect upstream emissions, including production and distribution of fuel or electricity*. Embodied life cycle emission factors must be used for vehicles and infrastructure produced, constructed, and utilized for the CO_2 removal project, and this must	Can be calculated using energy usage or distance-based methods.[234]

[228] VM0043 CO_2 Utilization in Concrete Production section 7
[229] Gold Standard Carbon Mineralization Using Reactive Mineral Waste, section 5.3
[230] Isometric Enhanced Weathering in Agriculture, section 7.1 table 1
[231] Puro Enhanced Rock Weathering, section 5.1
[232] Isometric Enhanced Weathering in Agriculture, section 7.4.3.5.2
[234] Isometric Transportation Emissions Accounting Module

	be calculated in addition to the Energy Usage or Distance-Based Methods.[233]	
Puro	Emissions from transporting ground material to its application site, including loading, transportation, and unloading, and all operations until the processed material is ready for application at the site[235].	LCI data which is ISO 14040/44 compliant.

Table A1-49. ERW energy (electricity and fuel) use emissions

Protocol	Scope	Data source requirement	Miscellaneous
Isometric	*The emissions associated with energy use must account for all operations that consume energy within the CDR project processes, through the usage of both electricity and fuel.* Electricity emission factors represent the life cycle of the fuel used to generate electricity and of the generator. [236]	If the project is grid powered, use *DOE National Transmission Needs Study* emission factor for grid electricity. No specific emission factor source is required for projects with PPA, but factors must include generation and fuel.[237]	Differentiates accounting for facilities consuming under (non-intensive) and over 200 GWh (intensive). Annual volumetric matching for non-intensive facilities, hourly volumetric for intensive. Waste heat can be used as a burden free energy input. [238]
Puro	Emissions from energy use for operations such as rock mining, grinding, transport and spreading. Must include emissions from production, installation, maintenance and disposal of generator[239].	None specified.	

Table A1-50. ERW operation and direct emissions

Protocol	Scope
Isometric	Emissions from sampling and analysis activities[240]. Must account for inorganic carbon loss due to soil column processes.
Puro	Emissions from mining of rock for ERW activity, processing of material, and all operations in the application stage[241]. Must

233 Isometric Transportation Emissions Accounting Module
235 Puro Enhanced Rock Weathering, section 5.1
236 Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
237 Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
238 Isometric Energy Use Accounting Module: https://registry.isometric.com/module/energy-use-accounting/1.2
239 Puro Enhanced Rock Weathering, section 6.5.1
240 Isometric Enhanced Weathering in Agriculture, section 7.1 table 1
241 Puro Enhanced Rock Weathering, section 5.1

	account for all losses due to subsequent chemical reactions in the environment[242]

Table A1-51. ERW end-of-life emissions

Protocol	Scope
Isometric	Emissions associated with equipment or infrastructure deconstruction[243].
Puro	Not included.

Table A1-52. ERW counterfactuals

Protocol	Scope	Data source requirement
Isometric	To be measured with a control plot. The counterfactual is the CO_2 removal that would have occurred from agricultural limiting in the absence of project activities. In some cases, the counterfactual of the feedstock is also relevant, that is the amount that would have been stored at the surface of the rock without intervention[244].	Calculated with a combination of direct measurements and models.
Puro	Weathering in a non-application plot[245].	Can be measured with plant cation uptake of the control plot[246].

Table A1-53. ERW economic leakage (market-mediated impacts)

Protocol	Scope
Isometric	Market leakage needs to be assessed, as a minimum feedstock replacement emissions need to be accounted for[247].
Puro	*May occur, primarily, if the weathering material (whether a primary product or a burden-free co-product) was already used to deliver another product or service, and thereby possibly entail the extraction of additional primary material, if demand persists*[248].

Table A1-54. ERW multifunctionality

Protocol	Scope

242 Puro Enhanced Rock Weathering, section 6.7.2
243 Isometric Enhanced Weathering in Agriculture, section 7.1 table 1
244 Isometric Enhanced Weathering in Agriculture, section 7.4.2
245 Puro Enhanced Rock Weathering, section 5.1
246 Puro Enhanced Rock Weathering, section 6.7.2
247 Isometric Enhanced Weathering in Agriculture, section 7.4.3.4
248 Puro Enhanced Rock Weathering, section 5.3

Isometric	In terms of co-product allocation, in the most conservative approach, CDR products will take full burden. Where processes are physically separable, processes that do not contribute to CDR can be excluded from the boundary.Where processes are not physically separable, the substitution method may be used to account for avoided emissions associated with the production of a co-product, only if these emissions are deemed *residual* or *hard-to-abate.* If co-product leads to CDR credit, allocation should be done based on carbon mass balance.[249]
Puro	*The two possible approaches for solving a multi-functionality issue, in the context of CORCs, are i) allocation of burdens between the co-products, and ii) cut-off approach (i.e. neglecting the co-products). The second approach is deemed more conservative and is simpler to implement*[250].

Table A1-55. ERW Net Removal Calculation

Protocol	Scope
Isometric	The gross CO_2 stored, minus the counterfactual, minus all project emissions, including losses[251].
Puro	The gross CO_2 stored, minus the emissions from the project, minus the leakage, minus the soil carbon loss[252].

Table A1-56. ERW feedstock eligibility

Protocol	Feedstock Eligibility
Isometric	No feedstock from carbonate sources is permitted. Feedstocks from mining waste can be used but might require further characterization to comply with local regulations. Homogeneity within a batch needs to be proved through characterization.[253]
Puro	Weathering materials with limited concentration of heavy metals. A geochemical assay must be conducted at least once per every 5000t of weathering material and *shall at least encompass* the particle size distribution, chemical oxide composition, Mineralogy and minor and major chemical elements. [254].

Table A1-57. ERW baseline definitions

Protocol	Baselines

[249] Isometric GHG Accounting Module section 6.1
[250] Puro Enhanced Rock Weathering, section 5.1.6
[251] Isometric Enhanced Weathering in Agriculture, section 7.3
[252] Puro Enhanced Rock Weathering, section 6.1
[253] Isometric Rock and Mineral Characterization Module
[254] Puro Enhanced Rock Weathering, section 4.2 and 7.4.4

Isometric	Soil prior to rock or mineral spreading. Targets to quantify soil heterogeneity, including pH, soil texture, soil permeability, cation exchange capacity and base saturation [255]
Puro	Soil carbon removal in the absence of ERW activities[256].

Table A1-58. ERW storage durability, permanence, and timing of carbon removals

Protocol	Durability Requirements
Isometric	At least 10,000 years[257].
Puro	Not addressed.

Table A1-59. ERW additionality requirements

Protocol	Additionality
Isometric	Financial, Regulatory, Market Adoption and Environmental. [258]
Puro	Financial and Regulatory[259]

[255] Isometric Enhanced Weathering in Agriculture, section 9.3.4.3
[256] Puro Enhanced Rock Weathering, section 3.2
[257] Isometric Enhanced Weathering in Agriculture, section 9.1
[258] Isometric Enhanced Weathering in Agriculture, section 6.4
[259] Puro Enhanced Rock Weathering, section 3.2

Appendix 2: Data and Modeling Assumptions

Life-Cycle and Net Flux Framework Accounting Methods Produce Different Carbon Removal Outcomes

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1. Data for assessing upstream systems

The biomass carbon removal and storage (BiCRS) scenarios involve various upstream systems as shown in Figure 1b-1f. This includes corn cultivation and harvesting (Figure 1b and 1e), wood harvesting during sustainable forest management (Figure 1c and 1d), sawmill operations (Figure 1d), and switchgrass cultivation and harvesting (Figure 1f). For woody biomass harvested during sustainable forest management, we use a carbon intensity of about 18.5 kg CO2eq. per tonne of wood from Zhang et al. (2016).[1] This carbon intensity describes shelterwood logging of natural hardwoods and does not include land use change which is difficult to estimate for managed forestry operations. For all other biomass resources (e.g., corn, corn stover, sawmill residues and switchgrass), we evaluate carbon intensities using Agile-Cradle-to-Grave (Agile-C2G), a physical units-based input–output life-cycle inventory model. Material and energy balances for corn cultivation and harvesting, sawmill operations, and switchgrass cultivation and harvesting are reported in Tables A2-1, A2-2, and A2-3, respectively. See Section 4 of this appendix for additional Agile-C2G data.

Table A2-1. GREET data for corn cultivation and harvesting[2]

Inputs	Value	Unit
Farming energy use (assume diesel)	3.68E+02	MJ
Nitrogen (assume urea)	1.56E+01	kg
P_2O_5	5.24E+00	kg
K_2O	5.43E+00	kg
$CaCO_3$	5.79E+01	kg

Herbicide (assume 50/50 atrazine/glyphosate)	3.02E-01	kg
Insecticide (assume negligible)	1.57E-03	kg
Outputs	**Value**	**Unit**
Corn	1.00E00	tonne
Corn stover (total above-ground biomass)	1.00E00	tonne
Soil Emissions	**Value**	**Unit**
N content of biomass	5.57E+00	kg per tonne of corn
N in N_2O emissions as % of N in N fertilizer and biomass	1.26%	%
N_2O emissions	2.68E-01	kg N_2O per tonne of corn

Table A2-2. Saw mill mass and energy balance from Khatri et al. (2025)[3]

Inputs	Value	Unit
Logs	1.82E+00	m3
Transportation (assume flatbed truck)	7.09E+01	tkm
Diesel	1.23E+00	L
Gasoline	1.20E-01	L
Natural gas	1.70E-02	m3
Propane (assume liquified petroleum gas)	2.70E-02	L
Electricity	3.78E+01	kWh
Outputs	**Value**	**Unit**
Rough green lumber	1.00E+00	m^3
Residues	3.11E+02	kg

Table A2-3. GREET data for switchgrass cultivation and harvest[2]

Inputs	Value	Unit
Farming energy use (assume diesel)	6.90E+01	MJ
Nitrogen (assume urea)	4.73E+00	kg
P_2O_5	2.24E+00	kg
K_2O	3.10E+00	kg
$CaCO_3$	5.67E+00	kg
Herbicide (assume 47/53 split between glyphosate and atrazine)[4]	5.15E-02	kg
Outputs	**Value**	**Unit**

Switchgrass	1	dry tonne
Soil Emissions	**Value**	**Unit**
N content of biomass	5.37E-01	kg per tonne of switchgrass
N in N_2O emissions as % of N in N fertilizer and biomass	1.26%	%
N_2O emissions	2.09E-01	kg N_2O tonne of switchgrass

2. BECCS Modeling

For both bioenergy with CCS (BECCS) scenarios (Figure 1d and 1e), we use a simplified model to estimate facility-level input output data reported in Table 2 of the main text. We assume a 50 MW plant with a capacity factor of 85%. Total power generation is therefore 372,300 MWh/year for both scenarios (Equation 1).

Power generation (MWh) = Capacity * Capacity Factor * Hours (per year) *(1)*

To estimate the electricity consumed by the CCS unit versus electricity exported to the grid, we assume that the CCS has a parasitic load share of 29%.[5] For our modeling purposes, this means that 29% of the carbon emissions associated with the BECCS plant (including those associated with raw material production, land use change and transportation) are allocated to the energy consumption in the activity-level LCA. In addition to energy allocation which is applied in the main activity-LCA results, we also show results applying the average U.S. grid intensity (see Figure 2 and 3 in the main text).

To estimate the annual feedstock loading rate for each BECCS scenario (Equation 2), we consider a facility thermal efficiency of 27%[6,7] and the energy content of the relevant feedstock (assume HHV) (Table A2-4).

Feedstock demand = [Power generation / Thermal efficiency] / Feedstock energy content *(2)*

Table A2-4. Biomass Characteristics from Kiprop Limo et al. (2024)[8]

	Sawdust Residue	Corn Stover	Unit
Carbon Content	47.16	39.54	%
HHV	17.93	17.38	MJ/kg

The total CO_2 removal potential (Equation 3) is estimated based on feedstock demand and the carbon content of the relevant feedstocks (Table A2-4). To estimate carbon storage for each BECCS scenario (Equation 4), we assume a post-combustion CO_2 capture rate of 90%.[9]

$$CO_2 \text{ removal potential} = \text{feedstock demand} * \text{C content of feedstock} * \text{mass factor ratio of } CO_2\text{:C} \quad (3)$$

$$\text{Gross carbon storage} = CO_2 \text{ removal potential} * CO_2 \text{ capture rate} \quad (4)$$

3. Summary of Modeling Assumptions

Table A2-5. Modeling assumptions for DACS scenarios

Category	Modeling description	
	DACS 1: Solvent-based DACS	**DACS 2: Sorbent-based DACS**
Gross carbon storage	This describes the quantity of CO2 injected underground for geologic sequestration. It does not include leaks post-capture.	
Emissions associated with energy inputs (electricity & fuels)	Energy inputs for this scenario include electricity and natural gas. Emissions associated with production of these energy inputs are accounted for using Agile-C2G and associated LCA data reported in Section 4. Natural gas is combusted for energy. Combustion emissions are not included as they are assumed to be captured alongside atmospheric CO_2. Leakage of natural gas-based CO_2 from storage is assumed to be negligible. Carbon equivalence of energy inputs is assessed with Agile-C2G and the data reported in Section 4.	The only energy input for this scenario is electricity. We use the US average grid carbon intensity for the carbon equivalence of this energy input. See data reported in Section 4.
Emissions associated with key materials	Key materials for this scenario include $CaCO_3$ and KOH. Embodied emissions in these materials are evaluated using Agile-C2G and associated LCA data reported in Section 4.	The key material for this scenario is amine-functionalized polymer sorbent. The carbon equivalence of this is adapted from Hanes et al. (2026). [10]
Carbon storage reversal	Reversal emissions are estimated assuming a 0.003% leakage rate from storage.[11,12]	

Table A2-6. Modeling assumptions for BiCRS scenario 1: corn-to-ethanol biorefinery with carbon capture and storage (CCS)

Category	Modeling description
Gross carbon storage	This describes the quantity of biogenic CO_2 injected underground for geologic sequestration. It does not include leaks post-capture. It does not include the capture of fossil-based CO_2 emissions from fuel combustion.
Land use change	This includes emissions associated with land use change for corn

	cultivation. To evaluate the relevant CO2e impacts, we use values adapted from GREET as per guidelines from the U.S. Department of Energy.[13]
Feedstock emissions	This includes emissions associated with corn cultivation (e.g., fuel combustion emissions, embodied emissions in fuels and materials, and soil emissions) excluding land use change which is reported on separately (see above). Input-output data for corn cultivation and soil emissions data is adapted from GREET (see Section 1 of this appendix).[2]
Facility-level emissions	This includes emissions from on-site combustion of natural gas that are not captured by the CCS unit.
Emissions associated with energy inputs (electricity & fuels)	Energy inputs for this scenario include electricity and natural gas. Emissions associated with production of these energy inputs are accounted for using Agile-C2G and associated LCA data reported in Section 4.
Carbon storage reversal	Reversal emissions from geologic storage are estimated assuming a 0.003% leakage rate.[11,12]
Transportation emissions	We assume 80 km distance for transportation of corn to the ethanol biorefinery. We assume the transportation method is flatbed trucking. Trucking emissions are evaluated using Agile-C2G and associated LCA data reported in Section 4.

Table A2-7. Modeling Assumptions for BiCRS Scenario 2: Pulp mill with CCS

Category	Modeling description
Gross carbon storage	This describes the quantity of biogenic CO_2 injected underground for geologic sequestration. It does not include leaks post-capture. It does not include the capture of fossil-based CO_2 emissions from fuel combustion.
Land use change	We assume that forests are sustainably managed and do not include any land use change for this scenario. We make this assumption in part because of the lack of reliable data related to the emissions impact of land use change for sustainably managed forests.
Feedstock emissions	This includes emissions associated with harvesting woody biomass. The carbon equivalence of harvested woody biomass is adapted from Zhang et al. (2016).[1] See Section 1 of this appendix for further details.
Facility-level emissions	All fuel combustion emissions are assumed to be captured by the CCS unit but fossil emissions are not credited in accounting of gross carbon storage.
Emissions associated with energy inputs (electricity & fuels)	The only energy input for this scenario is heavy fuel oil. We use residual fuel oil as a proxy for heavy fuel oil. Production emissions of the fuel are evaluated with Agile-C2G and associated LCA data

	reported in Section 4.
Carbon storage reversal	Reversal emissions from geologic storage are estimated assuming a 0.003% leakage rate.[11,12]
Transportation emissions	We assume 80 km distance for transportation of woody biomass to the pulp mill. We assume the transportation method is flatbed trucking. Trucking emissions are evaluated using Agile-C2G and associated LCA data reported in Section 4.

Table A2-8. Modeling Assumptions for BiCRS Scenario 3: BECCS with sawmill residues

Category	Modeling description
Gross carbon storage	This describes the quantity of biogenic CO_2 injected underground for geologic sequestration. It does not include leaks post-capture. It does not include the capture of fossil-based CO_2 emissions from fuel combustion.
Land Use Change	We assume that woody biomass used by the sawmill upstream of the BECCS facility is the same as that used in the previous scenario (pulp mill w/ CCS). See relevant assumptions in Table AS-7 for explanation of exclusion.
Feedstock Emissions	The feedstock for this scenario is sawmill residues. Associated emissions include sawmill operations and upstream woody biomass harvesting. We use the same assumptions from the previous scenario (pulp mill w/ CCS) to evaluate wood harvesting upstream of the sawmill. Sawmill operations are evaluated using the data in Section 1 of this appendix and Table A2-2.
Emissions Associated with Energy Inputs (Electricity & Fuels)	The BECCS facility is net-energy producing. The primary fuel is the biomass feedstock and we assume other energy inputs are negligible.
Carbon Storage Reversal	Reversal emissions from geologic storage are estimated assuming a 0.003% leakage rate.[11,12]
Transportation Emissions	We assume 80 km distance for transportation of sawmill residues to the BECCS facility. We assume the transportation method is flatbed trucking. Trucking emissions are evaluated using Agile-C2G and associated LCA data reported in Section 4. Upstream transportation of woody biomass to the sawmill is included in feedstock emissions.

Table A2-9. Modeling Assumptions for BiCRS Scenario 4: BECCS with corn stover

Category	Modeling Description
Gross Carbon Storage	This describes the quantity of CO_2 injected underground for geologic sequestration. It does not include leaks post-capture.
Land Use Change	This includes land use change associated with corn cultivation. To

	evaluate the relevant CO_{2e} impacts, we use values adapted from GREET as per guidelines from the U.S. Department of Energy.[13]
Feedstock Emissions	This includes emissions associated with corn cultivation (e.g., fuel combustion emissions, embodied emissions in fuels and materials, and soil emissions) excluding land use change which is reported on separately (see above). Input-output data for corn cultivation and soil emissions data is adapted from GREET (see Section 1 of this appendix).[2] No allocation is used to attribute away emissions to the primary corn product vs. corn stover. We assume that 30% of corn stover can be harvested sustainably.[14]
Emissions Associated with Energy Inputs (Electricity & Fuels)	The BECCS facility is net-energy producing. The primary fuel is the biomass feedstock and we assume other energy inputs are negligible.
Carbon Storage Reversal	Reversal emissions from geologic storage are estimated assuming a 0.003% leakage rate.[11,12]
Transportation Emissions	We assume 80 km distance for transportation of corn to the ethanol biorefinery.

Table A2-9. Modeling Assumptions for BiCRS Scenario 5: Pyrolysis of switchgrass for biochar production

Category	Modeling Description
Gross Carbon Storage	This describes the quantity of CO_2 equivalence of the carbon in produced biochar.
Land Use Change	We do not include land use change associated with switchgrass cultivation due to data scarcity and uncertainty.
Feedstock Emissions	This includes emissions associated with switchgrass cultivation (e.g., fuel combustion emissions, embodied emissions in fuels and materials, and soil emissions). Input-output data for corn cultivation and soil emissions data is adapted from GREET (see Section 1 of this appendix).[2]
Facility-Level Emissions	This includes emissions from on-site combustion of natural gas.
Emissions Associated with Energy Inputs (Electricity & Fuels)	The only energy input for this scenario is natural gas. Associated production emissions are evaluated with Agile-C2G and relevant LCA data reported in Section 4.
Carbon Storage Reversal	We assume that 20% of carbon in biochar is labile and emitted back to the atmosphere as CO_2 in the first few years after application.[15]
Transportation Emissions	We assume 80 km distance for transportation of switchgrass to the pyrolysis facility.

Table A2-10. Modeling Assumptions for Land-Based Mineralization Scenarios

Category	Modeling Description	
	Mineralization 1: Greenhouses	Mineralization 2: Tilling
Gross Carbon Storage	This includes CO_2 drawdown into stable carbonates during the removal timeframe of 100 years. Site-specific and method-specific estimates are adapted from Schmidt et al. (2026).[16]	
Land Use Change	Site-specific and method-specific land use change estimates are adapted from Schmidt et al. (2026).[16]	
Counterfactual Storage	This accounts for mineralization that would have taken place in the absence of the CDR intervention. Site-specific counterfactual storage estimates are adapted from Schmidt et al. (2026).[16]	
Facility-Level Emissions	There are no on-site combustion emissions for this scenario.	This includes diesel combustion emissions.
Emissions Associated with Energy Inputs (Electricity & Fuels)	We assume all equipment in this scenario is electrified so the only energy input is electricity. We use the US average grid carbon intensity for the carbon equivalence of this energy input. See data reported in Section 4.	We assume mining, transport and mixing equipment in this scenario is diesel-powered, while grinding equipment is electric. The energy inputs for this scenario therefore include diesel and electricity. We use the US average grid carbon intensity for the carbon equivalence of electricity. See data reported in Section 4. Diesel production emissions are evaluated with Agile-C2G and relevant LCA data reported in Section 4.
Carbon Storage Reversal	We assume that mineralized carbon is highly stable and has negligible risk of reversal during the removal timeframe.	

4. LCA Data for Material and Energy Inputs

We use the Agile-C2G LCA model and associated data previously documented in Nordahl et al. (2025)[17] to assess the embodied emissions in materials and energy consumed across the system supply chain for each scenario. Relevant data is re-reported in Tables A2-11 and A2-12 below.

Table A2-11. LCA Data: Emission Factors

All values are in units of kg of pollutant (given by column name) per unit indicated at the end of the unit process name. These are not necessarily life-cycle emission factors and only definitely include direct emission impacts (in several cases, this means fugitive emissions associated with fuel combustion); full life-cycle impacts must be assessed through the model using this data along with IO data from Table S6. When possible, GHG emission factors are separated by pollutant type; in cases where this is not possible, total GHG impact in CO_2 equivalence is given by the CO_2 column while the CH_4 and N_2O columns are marked with zeros. Zero entries can indicate no direct emissions, negligible direct emissions or unknown direct emissions.

Unit process	CO_2	CH_4	N_2O	Source(s)
atrazine.kg	8.71E+00	1.56E-04	1.25E-04	[18]
glyphosate.kg	0.00E+00	0.00E+00	0.00E+00	NA
CaCO3.kg	1.61E-03	5.15E-08	3.19E-08	[18]
K2O.kg	4.50E-01	8.91E-04	7.64E-06	[19]
urea.kg	3.57E-01	1.11E-03	9.71E-06	[19]
P2O5.kg	6.74E-02	1.29E-04	1.04E-06	[19]
coal.MJ	6.97E-04	1.39E-04	8.73E-09	[19]
diesel.MJ	5.09E-03	3.93E-08	2.02E-07	[18]
RFO.MJ	4.00E-03	8.74E-06	6.83E-08	[20]
refgas.MJ	7.06E-02	0.00E+00	0.00E+00	[19]
crudeoil.MJ	2.62E-03	8.24E-05	3.12E-08	[20]
electricity.US.kWh	4.14E-01	4.40E-05	7.00E-06	[21]
gasoline.MJ	3.56E-03	3.48E-05	1.32E-07	[20]
H2.kg	1.06E+01	5.98E-02	4.00E-05	[22]
Naturalgas. conventional.MJ	4.06E-03	8.70E-05	2.60E-08	[18]
Naturalgas. shale.MJ	3.80E-03	9.19E-05	2.59E-08	[18]
naturalgas_select.MJ	0.00E+00	0.00E+00	0.00E+00	NA; Selection variable with IO references to shale and conventional production shares
flatbedtruck.mt_km	1.24E-01	0.00E+00	0.00E+00	[23]
tankertruck.mt_km	8.46E-02	0.00E+00	0.00E+00	[23]
liquidpipeline.mt_km	0.00E+00	0.00E+00	0.00E+00	NA
rail.mt_km	1.86E-02	0.00E+00	0.00E+00	[23]
barge.mt_km	2.22E-02	0.00E+00	0.00E+00	[23]
marinetanker.mt_km	6.91E-03	8.02E-08	0.00E+00	[23]
butane.MJ	5.16E-03	2.24E-07	4.35E-08	[24]
lpg.kg	5.22E-01	1.45E-03	8.28E-06	[24]
KOH.kg	1.73E-01	3.09E-06	1.78E-06	[21]
KCl.kg	1.82E-01	3.28E-06	2.92E-06	[21]
urea_application.kg	0.00E+00	0.00E+00	6.35E-03	[25,26]

Table A2-12. LCA Model: Input-Output Matrix Relationships

Our LCA model uses a physical units-based input-output matrix that is populated with life-cycle inventories for each unit process/product included. The relevant non-zero values are included in this table. Each unit process/product is listed with a unit. The value indicates the amount of the upstream/downstream requirement in its listed unit required to make 1 unit of the primary unit product/process. For unit processes from Table S5 that are not included in this table, there are either (1) no upstream/downstream impacts for that parameter or (2) insufficient input/output data is available and full life-cycle emissions are included in the emission factors in Table S5.

Unit process	Life-cycle requirements	Value	Units	Source
atrazine				
	diesel	4.41E+01	MJ/kg	[18]
	RFO	4.41E+01	MJ/kg	[18]
	electricity.US	6.94E+00	kWh/kg	[18]
	natural gas_select	3.38E+01	MJ/kg	[18]
	tanker truck	4.26E-01	mt_km/kg	[19]
	rail	1.26E+00	mt_km/kg	[19]
glyphosate				
	tankertruck	4.26E-01	mt_km/kg	[19]
	rail	1.26E+00	mt_km/kg	[19]
CaCO3				
	coal	3.66E-03	MJ/kg	[18]
	diesel	1.30E-02	MJ/kg	[18]
	RFO	1.64E-03	MJ/kg	[18]
	electricity.US	2.44E-04	kWh/kg	[18]
	gasoline	2.56E-03	MJ/kg	[18]
	naturalgas_select	1.22E+00	MJ/kg	[18]
	flatbedtruck	8.00E-02	mt_km/kg	[19]
K2O				
	diesel	2.40E+00	MJ/kg	[19]
	naturalgas_select	2.70E+00	MJ/kg	[19]
	tankertruck	4.26E-01	mt_km/kg	[19]
	rail	1.26E+00	mt_km/kg	[19]
urea				
	electricity.US	1.29E+00	kWh/kg	[18]
	naturalgas_select	5.16E+00	MJ/kg	[18]
	tankertruck	4.26E-01	mt_km/kg	[19]
	rail	1.26E+00	mt_km/kg	[19]
P2O5				
	diesel	3.90E+00	MJ/kg	[19]
	naturalgas_select	1.50E+00	MJ/kg	[19]

	tankertruck	4.26E-01	mt_km/kg	[19]
	rail	1.26E+00	mt_km/kg	[19]
coal				
	diesel	2.30E-03	MJ/MJ	[19]
	RFO	2.53E-04	MJ/MJ	[19]
	electricity.US	2.09E-03	kWh/MJ	[19]
	gasoline	1.89E-04	MJ/MJ	[19]
	naturalgas_select	5.82E-05	MJ/MJ	[19]
	flatbedtruck	2.55E-03	mt_km/MJ	[19]
	rail	5.34E-02	mt_km/MJ	[19]
	barge	2.24E-02	mt_km/MJ	[19]
diesel				
	RFO	3.11E-02	MJ/MJ	[18]
	refgas	5.81E-02	MJ/MJ	[18]
	crudeoil	1.00E+00	MJ/MJ	[18]
	electricity.US	8.93E-04	kWh/MJ	[18]
	H2	1.08E-04	kg/MJ	[18]
	naturalgas_select	5.19E-02	MJ/MJ	[18]
	tankertruck	3.53E-03	mt_km/MJ	[18]
	liquidpipeline	2.10E-02	mt_km/MJ	[18]
	butane	9.92E-05	MJ/MJ	[18]
RFO (residual fuel oil)				
	RFO	2.70E-02	MJ/MJ	[18]
	refgas	3.73E-02	MJ/MJ	[18]
	crudeoil	1.00E+00	MJ/MJ	[18]
	electricity.US	3.71E-04	kWh/MJ	[18]
	H2	1.20E-05	kg/MJ	[18]
	naturalgas_select	2.43E-02	MJ/MJ	[18]
	tankertruck	3.53E-03	mt_km/MJ	[18]
	liquidpipeline	2.10E-02	mt_km/MJ	[18]
	butane	7.20E-05	MJ/MJ	[18]
refgas				
	crudeoil	1.00E+00	MJ/MJ	NA
crudeoil				
	diesel	3.06E-03	MJ/MJ	[18]
	RFO	2.04E-04	MJ/MJ	[18]
	crudeoil	2.04E-04	MJ/MJ	[18]
	electricity.US	1.08E-03	kWh/MJ	[18]
	gasoline	4.08E-04	MJ/MJ	[18]
	naturalgas_select	1.26E-02	MJ/MJ	[18]

	tankertruck	5.49E-03	mt_km/MJ	18
	liquidpipeline	2.85E-02	mt_km/MJ	18
	rail	2.42E-02	mt_km/MJ	18
	barge	4.39E-03	mt_km/MJ	18
	marinetanker	1.10E-01	mt_km/MJ	18
gasoline				
	RFO	9.28E-02	MJ/MJ	27
	refgas	9.26E-02	MJ/MJ	27
	crudeoil	1.00E+00	MJ/MJ	27
	electricity.US	1.44E-02	kWh/MJ	27
	H2	5.26E-05	kg/MJ	27
	naturalgas_select	6.27E-02	MJ/MJ	27
	tankertruck	3.53E-03	mt_km/MJ	27
	liquidpipeline	2.10E-02	mt_km/MJ	27
	butane	6.44E-02	MJ/MJ	27
H2				
	electricity.US	2.69E-01	kWh/kg	22
	naturalgas_select	1.43E+02	MJ/kg	22
flatbedtruck				
	diesel	1.78E+00	MJ/mt_km	23
	flatbedtruck	2.50E-01	mt_km/mt_km	23
tankertruck				
	diesel	1.22E+00	MJ/mt_km	23
	tankertruck	2.50E-01	mt_km/mt_km	23
liquidpipeline				
	electricity.US	1.84E-02	kWh/mt_km	28
rail				
	diesel	2.68E-01	MJ/mt_km	23
	rail	2.50E-01	mt_km/mt_km	23
barge				
	diesel	3.20E-01	MJ/mt_km	23
	barge	2.50E-01	mt_km/mt_km	23
marinetanker				
	RFO	1.00E-01	MJ/mt_km	23
	marinetanker	2.50E-01	mt_km/mt_km	23
butane				
	naturalgas_select	1.00E+00	MJ/MJ	NA
KOH				
	diesel	1.41E+00	MJ/kg	21
	electricity.US	3.28E+00	kWh/kg	21

	naturalgas_select	1.22E+00	MJ/kg	21
	kcl	1.52E+00	kg/kg	21
KCl				
	RFO	1.41E+00	MJ/kg	21
	electricity.US	5.29E-01	kWh/kg	21
	naturalgas_select	1.22E+00	MJ/kg	21

5. Tabulated Results by Scenario

The following tables describe CO_2e fluxes associated with 1 standard year of operation for each scenario. Table A2-13 includes tabulated results for both DACS scenarios for which activity-level LCA and NFF results are the same. Tables A2-14 through A2-18 report results for BiCRS scenarios by framework and by category. Table A2-19 includes tabulated results for both mineralization scenarios for which activity-level LCA and NFF results are the same.

Table A2-13. Tabulated Results for DACS Scenarios

	DACS 1: Solvent-based DACS (tonnes CO_2e/year)	**DACS 2: Sorbent-based DACS (tonnes CO_2e/year)**
Gross Carbon Storage	8.00E+05	6.00E+05
Emissions Associated with Energy Inputs (Electricity & Fuels)	-1.88E+05	-4.05E+05
Emissions Associated with Key Materials	-1.77E+04	-4.31E+04
Carbon Storage Reversal	-2.40E+03	-1.80E+03
Summary Metrics		
Gross Storage	8.00E+05	6.00E+05
Net Carbon Benefit (activity-level LCA)	5.92E+05	1.50E+05
Net Removal (NFF)	5.92E+05	1.50E+05
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	73.94%	25.00%
Removal Efficiency (NFF)	73.94%	25.00%

Table A2-14. Tabulated Results for BiCRS Scenario 1: Corn-to-ethanol biorefinery with carbon capture and storage (CCS)

	NFF (tonnes CO_2e/year)	**LCA (tonnes CO_2e/year)**
Gross Carbon Storage	1.03E+05	1.03E+05
Land Use Change	-1.90E+04	0.00E+00
Feedstock Emissions	-7.75E+04	0.00E+00
Facility-Level Emissions	-6.64E+03	0.00E+00
Emissions Associated with Energy Inputs (Electricity & Fuels)	-6.01E+04	-1.35E+04
Carbon Storage Reversal	-3.09E+02	-3.09E+02
Transportation Emissions	-6.34E+03	0.00E+00

Avoided Emissions (coproduct)	NA	0.00E+00
Avoided Emissions (waste diversion)	NA	0.00E+00
Avoided Emissions (reduced soil emissions)	NA	0.00E+00
Summary Metrics		
Gross Storage	1.03E+05	
Net Carbon Benefit (activity-level LCA)	8.93E+04	
Net Removal (NFF)	-6.68E+04	
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	86.60%	
Removal Efficiency (NFF)	-64.73%	

Table A2-15. Tabulated Results for BiCRS Scenario 2: Pulp and paper mill with CCS

	NFF (tonnes CO_2e/year)	**LCA (tonnes CO_2e/year)**
Gross Carbon Storage	1.86E+06	1.86E+06
Feedstock Emissions	-5.16E+04	0.00E+00
Emissions Associated with Energy Inputs (Electricity & Fuels)	-2.11E+04	-3.04E+05
Carbon Storage Reversal	-5.57E+03	-5.57E+03
Transportation Emissions	-4.84E+04	0.00E+00
Summary Metrics		
Gross Storage	1.86E+06	
Net Carbon Benefit (activity-level LCA)	1.55E+06	
Net Removal (NFF)	1.73E+06	
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	83.37%	
Removal Efficiency (NFF)	93.19%	

Table A2-16. Tabulated Results for BiCRS Scenario 3: Bioelectricity production from sawmill residues with CCS

	NFF (tonnes CO_2e/year)	**LCA (tonnes CO_2e/year)**
Gross Carbon Storage	4.31E+05	4.31E+05
Feedstock Emissions	-4.97E+04	0.00E+00
Emissions Associated with Energy Inputs (Electricity & Fuels)	0.00E+00	-4.50E+04

Carbon Storage Reversal	-1.29E+03	-1.29E+03
Transportation Emissions	4.81E+03	0.00E+00
Summary Metrics		
Gross Storage	4.31E+05	
Net Carbon Benefit (activity-level LCA)	3.85E+05	
Net Removal (NFF)	3.85E+05	
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	89.24%	
Removal Efficiency (NFF)	89.27%	

Table A2-17. Tabulated Results for BiCRS Scenario 4: Bioelectricity production from corn stover with CCS

	NFF (tonnes CO_2e/year)	LCA (tonnes CO_2e/year)
Gross Carbon Storage	3.53E+05	3.53E+05
Land Use Change	-1.49E+04	0.00E+00
Feedstock Emissions	-2.02E+05	0.00E+00
Emissions Associated with Energy Inputs (Electricity & Fuels)	0.00E+00	-4.50E+04
Carbon Storage Reversal	-1.06E+03	-1.06E+03
Transportation Emissions	-4.96E+03	0.00E+00
Summary Metrics		
Gross Storage	3.53E+05	
Net Carbon Benefit (activity-level LCA)	3.07E+05	
Net Removal (NFF)	1.31E+05	
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	86.96%	
Removal Efficiency (NFF)	36.92%	

Table A2-18. Tabulated Results for BiCRS Scenario 5: Pyrolysis of switchgrass for biochar production

	NFF (tonnes CO_2e/year)	LCA (tonnes CO_2e/year)
Gross Carbon Storage	5.60E+04	5.60E+04
Feedstock Emissions	-8.05E+03	-8.05E+03
Facility-Level Emissions	-2.46E+02	-2.46E+02

Emissions Associated with Energy Inputs (Electricity & Fuels)	-3.43E+01	-3.43E+01
Carbon Storage Reversal	-1.12E+04	-1.12E+04
Transportation Emissions	-1.46E+03	-1.46E+03
Avoided Emissions (reduced soil emissions)	NA	7.50E+02
Summary Metrics		
Gross Storage	5.60E+04	
Net Carbon Benefit (activity-level LCA)	3.58E+04	
Net Removal (NFF)	3.50E+04	
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	63.86%	
Removal Efficiency (NFF)	62.52%	

Table A2-19. Tabulated Results for Mineralization Scenarios

	Mineralization 1: Greenhouse method with electrified equipment (tonnes CO_2e/year)	**Mineralization 2: Tilling method with diesel-powered equipment (tonnes CO_2e/year)**
Gross Carbon Storage	4.60E+05	1.04E+04
Land Use Change	-8.47E+02	-8.47E+02
Counterfactual Storage	-3.26E+03	-3.26E+03
Facility-Level Emissions	0.00E+00	-2.57E+03
Emissions Associated with Energy Inputs (Electricity & Fuels)	-1.39E+04	-9.10E+02
Summary Metrics		
Gross Storage	4.60E+05	1.04E+04
Net Carbon Benefit (activity-level LCA)	4.42E+05	2.81E+03
Net Removal (NFF)	4.42E+05	2.81E+03
Efficiencies		
Carbon Benefit Efficiency (activity-level LCA)	96.09%	27.01%
Removal Efficiency (NFF)	96.09%	27.01%

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