ERM

A Review of Engineered Greenhouse Gas Removal (GGR) Standards and Methodologies

A REPORT FOR THE UK DEPARTMENT FOR ENERGY SECURITY AND NET ZERO (DESNZ)

12/12/2023

Sustainability is our business

Authors and acknowledgements

This report was prepared by Element Energy and E4tech, who in June 2021 both joined the ERM Group, the largest sustainability consultancy, with a global footprint and over 7,000 employees worldwide.

We specialise in the intelligent analysis of low carbon energy, industrial decarbonisation, and low-carbon fuels. We provide consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport/fuels. In addition, we focus on both technical and strategic issues, and offer bespoke business and policy advice based on deep technical understanding, insightful analysis and industry knowledge.

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This study reviews existing and proposed MRV standards for engineered GGRs to understand their potential applicability for the UK

Background and context

Greenhouse gas removals* (GGR) result in a net reduction of atmospheric CO_2 through a variety of technologies which ensure long-term sequestration of carbon. GGRs are essential for limiting atmospheric CO_2 concentrations and achieving global temperature targets according to IPCC's Integrated Assessment Models. In its **Net Zero Strategy**, the UK Government declared an ambition to deploy 5 $MtCO_2$/year of engineered GGRs by 2030, which may increase to 23 $MtCO_2$/year by 2035.

Reaching these targets is expected to require comprehensive financial incentives (see **Element Energy**, 2022). Following a public consultation in 2022, the UK Government **announced** its intention to develop a business model for engineered GGRs based on carbon contracts for difference (CCfD). Furthermore, the UK Government is **considering eventual integration** of GGRs into the UK Emissions Trading Scheme (ETS).

Achieving these policy objectives requires robust accounting and monitoring, reporting and verification (MRV) standards for GGR projects. As a result, DESNZ commissioned this work to establish whether emerging GGR MRV standards adequately cover engineered GGR technologies and successfully address key lifecycle / MRV considerations.

Aim and objectives

Project aim: Deepen the UK Government's understanding of existing and proposed MRV frameworks for engineered GGRs, providing input into their potential applicability in the UK context.

Objectives:

- Summarise lifecycle analysis (LCA) and MRV considerations for different engineered GGR technologies (task 2).
- Review existing and proposed standards and methodologies for certification of the GGR technologies in scope (task 3).
- Assess how each GGR technology would be treated under these standards, including suitability of MRV frameworks to address key uncertainties (task 4).
- Assess the suitability of the standards for their application to GGR technologies by the UK Government and discuss potential implementation options (task 5).

Disclaimer – The analysis in this study is informed by the information available until mid-June 2023. The GGR certification space is dynamic and rapidly evolving. Several recent developments – such as DACCS and BECCS methodologies under the **CCS+ initiative**, Drax and Stockholm Exergi's standalone **BECCS methodology** and the **Isometric Standard** – are not included in the report.

*Also known as carbon dioxide removal (CDR) or negative emission technologies (NETs).

Overview of tasks and stakeholder engagement process

Task 1: Design and finalisation of the methodology

Task 2: Rapid technology assessment review to identify key LCA / MRV considerations

Task 3: Review existing / proposed GGR MRV standards and methodologies

Task 4: Assessment of treatment of GGR technologies within each scheme

Task 5: Assessing suitability of standards and methodologies for adoption by the UK Government in GGR policy

Continuous engagement with the project Steering Group, comprised of different governmental departments and external stakeholders

Phase 1: Targeted calls with academics with expertise in LCA / MRV of specific GGR technologies

Phase 2: Engagement with GGR MRV schemes to receive feedback on initial assessment of standards and methodologies

Phase 3: Discussion of draft outputs in a workshop with UK policymakers

Standards with specific MRV provisions for GGR technologies were reviewed and assessed at both the general standard and specific methodology level

- The scope of the study includes the following engineered GGR technologies: direct air capture with carbon storage (DACCS), bioenergy with carbon capture and storage (BECCS), biochar, enhanced rock weathering (ERW), ocean-based removals (Ocean GGRs) and carbon-negative building materials.
- The detailed review focused on existing and proposed standards and methodologies applicable to GHG accounting of GGR technologies. Priority was given to standards that included specific MRV requirements, followed by other GHG standards relevant for GGR technologies. The table below shows the standards and specific methodologies focused on in this study.
- Note that analysis was performed in mid-June 2023 and did not consider any updates introduced after this period, such as the **draft DACCS and BECCS methodologies** developed by CCS+ Initiative under Verra.

Standard	DACCS	BECCS	Biochar	EW	Oceans	Concrete
Puro Earth	Dark Green	Dark Green	Dark Green	Dark Green	Tan	Dark Green
Verra	Tan	Tan	Dark Green	Tan	Tan	Dark Green
Gold Standard	Tan	Dark Green	Tan	Tan	Tan	Dark Green
American Carbon Registry	Light Green	Light Green	Tan	Tan	Tan	Tan
Climate Action Reserve	Tan	Tan	Light Green	Tan	Tan	Tan
Climeworks, Carbfix	Dark Green					
Carbon Standards Int.	Tan	Tan	Dark Green	Dark Green	Tan	Tan
Planetary					Dark Green	

- General provisions of the standards in scope are presented using standardised templates. For each GGR standard with a publicly available MRV mechanism (green and brown boxes in the table), we analysed in depth how the key LCA / MRV considerations are addressed for each technology. This included a qualitative assessment of the key methodological provisions.
- After compilation of key information, each GGR standard and their technology-specific methodologies were qualitatively assessed. The table below summarises the definition of the criteria used.
- The following slides discuss the practical implications of different options for the UK Government, including the possibility to fully or partially endorse an existing standard/methodology, or to develop new ones

Criteria	Definition
Suitability of methodologies	Suitability of each of the methodologies to successfully address the key LCA and MRV considerations of GGR technologies.
Assurance	Level of assurance and reliability of reported GHG reductions from GGR activities, based on verification requirements.
Environmental and social safeguards	Inclusion of non-GHG sustainability and social safeguards, e.g., ecosystem/biodiversity, land rights, worker conditions, etc.
Credibility	Public perception, track record of grievance or negative comments from civil society organisation, governance (inclusiveness and transparency).
Governance	Existence of clear boundaries between the standard development process MRV implementation mechanisms, independent scientific advisory and includes multi stakeholder feedback in methodology development.

Colour code for table: Dark Green – existing methodologies; Light Green – publicly available draft methodologies under development; Tan – potential future methodology, but no public drafts or expansion plans; Blank – the standard is not expected to expand to other GGR technologies

The review of existing MRV methodologies and standards revealed that in their current state, none would be appropriate alone to cover all the engineered GGR technologies in scope

Are any of the methodologies suitable for any GGR technologies?

- **Few existing MRV methodologies** were deemed suitable for possible UK Government endorsement **in their current form** (before UK-specific policies are overlaid).
  - This reflects the developing nature of many of the GGR technologies reviewed, as standard practices and best available MRV techniques are still being determined.
  - The only methodologies which could be endorsed without significant revisions or expansions are Verra's biochar and the American Carbon Registry's DACCS methodologies.
  - Two other methodologies – Gold Standard methodologies for BECCS fermentation and carbonation of concrete aggregates – were found to be suitable for certifying their respective GGRs. However, these are currently restricted in scope and would require significant expansion to cover a larger number of GGR technologies.
- However, some of the methodologies rate **more favourably** and may be suitable for adoption by the UK Government if **existing UK standards and policies** (e.g., in CCS and biomass) are considered alongside the current GGR standards. These are Puro Earth's methodologies for DACCS, BECCS and biochar, Climeworks / Carbfix methodology for DACCS and Carbon Standards International methodology for biochar.
- Companies which have developed their own MRV methodologies for **specific projects** (Planetary, Climeworks / Carbfix, etc) provide a useful platform to further support the deployment of MRV schemes. However, these methodologies **lack the scope** required to become a governing standard, as they often only deal with a specific configuration within a GGR technology.
- **Other standards** (Microsoft, Shopify, XPRIZE, etc) provide useful overviews of additional MRV considerations for individual GGR technologies and projects. However, endorsing or adopting these as an MRV standard **would be challenging**, as many are merely assessment criteria for credit purchases rather than true MRV standards.
- **The standards sector for GGR MRVs is evolving rapidly**, with multiple new methodologies and updates published while this study was conducted. As a result, the conclusions in this report are subject to market evolution and may need to be revisited in the future.

Each of the five identified options for MRV development have accompanying advantages and drawbacks which would need to be carefully considered

1 Endorsement of a single standard

Pros
- Relatively administratively simple
- Leverages existing experience and knowledge of private standards, including the validation and verification bodies (VVBs) that carry out assessments

Cons
- No suitable standard to certify all GGR technologies in scope
- Over-reliance on one standard, which may change in scope and provisions
- Higher credibility risk exposure from a single partner

2 Endorsement of multiple standards

Pros
- Relatively administratively simple
- Leverages existing experience and knowledge of private standards, including VVBs that carry out assessments
- Combines the most suitable methodologies from different sectors

Cons
- May be confusing for some stakeholders
- Limited / no influence over how methodologies may change in the future
- Credibility risk is more spread, but still present

3 Partnership with standard(s) to develop joint methodologies

Pros
- Larger flexibility with tailoring methodologies
- Leverages existing experience and knowledge of private standards, including VVBs that carry out assessments

Cons
- HMG may need to provide financial contributions to the standards for expansion of methodologies
- More administratively complex than direct endorsements
- May lead to standards / methodologies inflation in the GGR sector (minor)

4 Development of an independent new GGR MRV standard

Pros
- Can be tailored for UK Government's requirements and context
- Likely to carry high credibility since it will be a public scheme, although some risk exists if external standards are used for administration.
- May be inspired by best examples from other standards
- No need to make financial contributions to third parties if the UK Government takes on the administration task

Cons
- Administratively complex – likely requires significant scientific and stakeholder input, which can be time consuming
- May lead to standards / methodologies inflation in the GGR sector (minor)
- VVBs would need to be trained to get familiar with the scheme, especially if the UK Government takes on the administration task

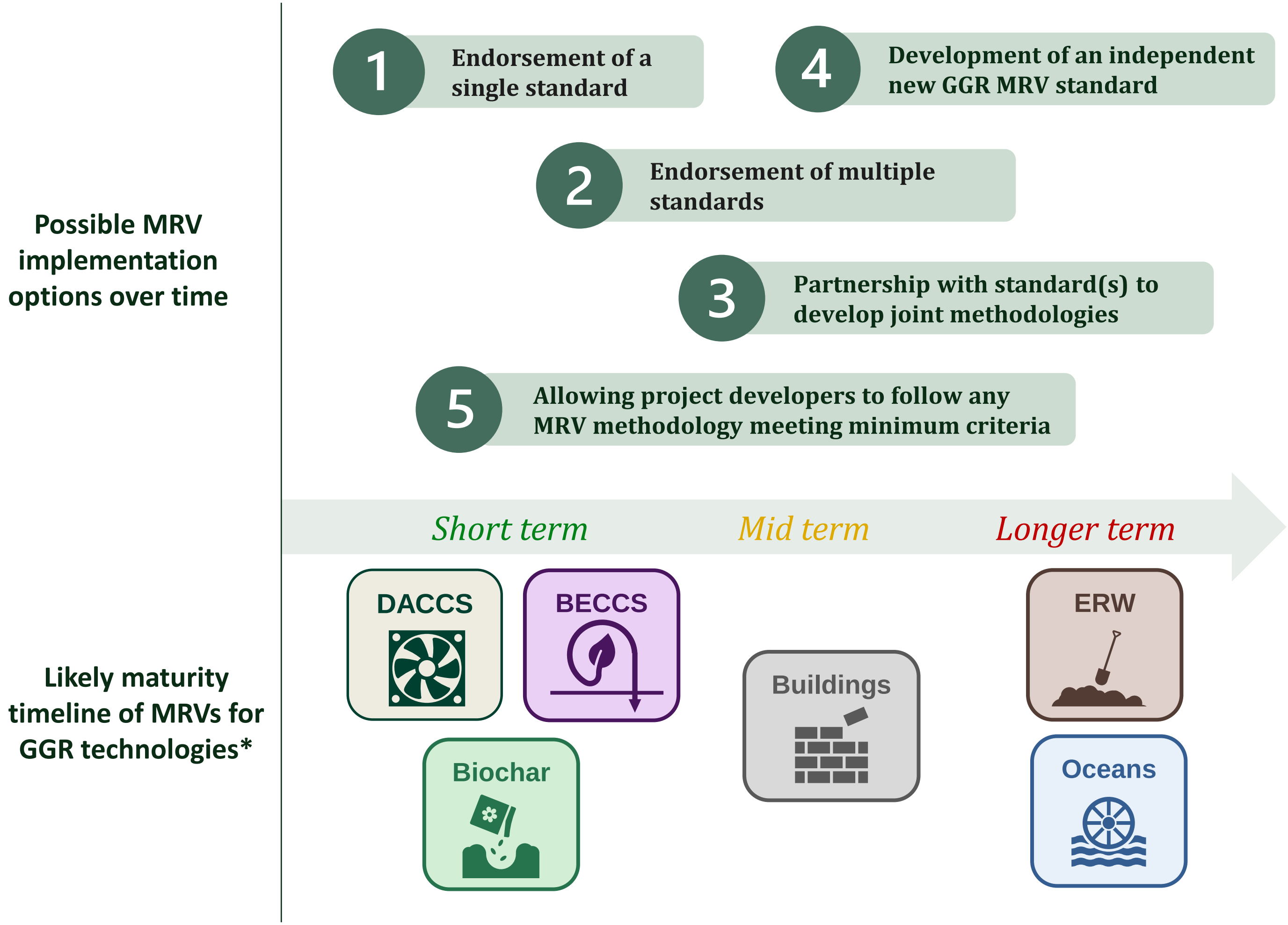
5 Allowing any MRV methodology that satisfies minimum criteria

Pros
- Additional flexibility to accommodate less mature GGR technologies
- Allows government to take most appropriate practices from a variety of methodologies, without having to transpose the entire standard
- Can be implemented relatively quickly for early projects
- Presents a consistent framework for consideration of different MRV standards, although individual GGR projects would still be treated slightly differently as they can follow different standards.

Cons
- Can be administratively burdensome, especially in the long term, since each MRV standard submitted would have to be assessed.
- May lead to standards / methodologies inflation in the GGR sector (minor)

Some MRV options can be implemented faster than others and allow for a transition between options, matching future development of GGR technologies

- Different MRV development options could be implemented based on the priorities and capabilities of the UK Government and technical maturity of different GGRs.
  - Endorsing one or more standards (options 1 and 2) or developing minimum criteria (option 5) could be done in the shorter term, with a possible transition to an independent standard (option 4) in the long-term.
- This also gives the UK Government flexibility when engaging with GGR technologies at different maturity levels.
  - Developing a new methodology for less commercially-ready technologies (ocean GGRs and ERW) would be more challenging, meaning setting minimum criteria (option 5) might be necessary to give greater flexibility as experience develops.
  - This may contrast with more commercially-ready technologies (such as DACCS and BECCS), where it would be more feasible to develop or endorse more detailed methodologies earlier.



* Note that this timeline only includes the six engineered GGRs focused on in this study, however, MRV frameworks for other engineered GGRs (e.g., biomass burial, bio-oil injection, etc.) could also be developed.

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Report structure

This report presents the study outputs in the following structure:

- **Task 2 – technology rapid assessment review** presents an overview of the technologies, key MRV / LCA considerations for each technology and common methods for measurement and accounting of GHG impacts.
- **Tasks 3 & 4 – GGR standards and methodologies review** presents a review of existing / proposed GGR MRV standards and assessment of treatment of each of the technologies by these frameworks.
- **Task 5 – assessment of standards and conclusions** provides standard-level and methodology-level assessments for the schemes considered and provides a discussion of potential adoption options.

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Approach to task 2: rapid review of key LCA / MRV considerations for engineered GGR technologies

Objectives / scope

- In this task we provided an overview of key cradle-to-grave LCA considerations for each of the GGR technologies in scope, including key uncertainties. The aim of this was to underpin our following assessment of how comprehensively and appropriately each MRV methodology took these factors into account.
- Technologies in scope:

1. Direct air capture and carbon storage (DACCS)
2. Bioenergy with carbon capture and storage (BECCS)
3. Biochar
4. Enhanced rock weathering (ERW)
5. Ocean GGRs (ocean alkalinity enhancement and direct ocean capture)
6. Carbonated building elements, including carbon negative concrete

- For technologies with multiple configurations (such as BECCS power, BECCS hydrogen, BECCS energy from waste) we presented generalised elements of these configurations (such as co-products) and discussed how LCA / MRV considerations may apply differently to these elements.

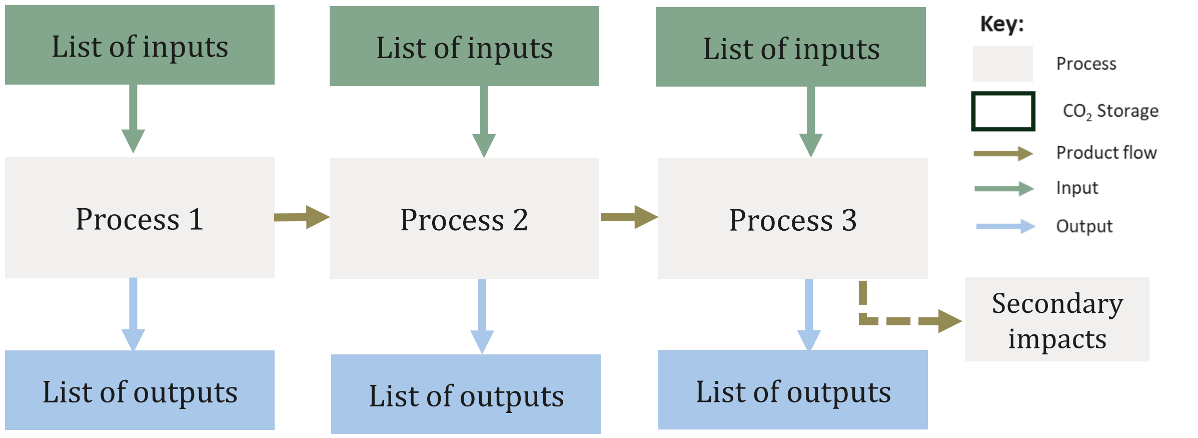
Stakeholder engagement phase 1: We had two targeted engagement calls with academic experts on enhanced rock weathering and ocean removals technologies. This enabled us to identify and address gaps in our initial assessment and determine the key methodological uncertainties for these GGRs.

Outputs of this section

For each GGR technology, Task 2 delivered the following outputs:

- Description of technology
- Technology process flow diagrams (see example below)
- High level overview of lifecycle LCA results reported in the literature and references to key sources, including discussion of limitations of existing literature. It is important to note that methodological differences between results means they will not be comparable between technologies
- Summary table of key LCA methodological questions, related uncertainties and likely impact of elements with high uncertainties
- Summary table of direct/indirect measurement options of inputs and outputs
- Final summary table of key uncertainties and points of consideration for review of GGR standards in the following tasks

Illustrative schematic of technology flow diagrams



General lifecycle analysis (LCA) considerations applicable to most GGR projects

Lifecycle analysis (LCA) is a methodological approach used to assess the environmental impacts (incl. GHG emissions, resource depletion, ecotoxicity, etc) of a product or service over its entire life-cycle. Verifying the accuracy and robustness of an LCA requires clear rules for Monitoring, Reporting and Verification (MRV). This is particularly the case in the GGR context, where GHG calculations need to be accurately measured (or estimated), reported and verified to offer sufficient assurance over carbon removals and related credits. The credible and robust deployment of GGR technologies therefore rely on the complementarity between GHG LCA (GHG accounting methodology) and MRV (assurance over accuracy and robustness).

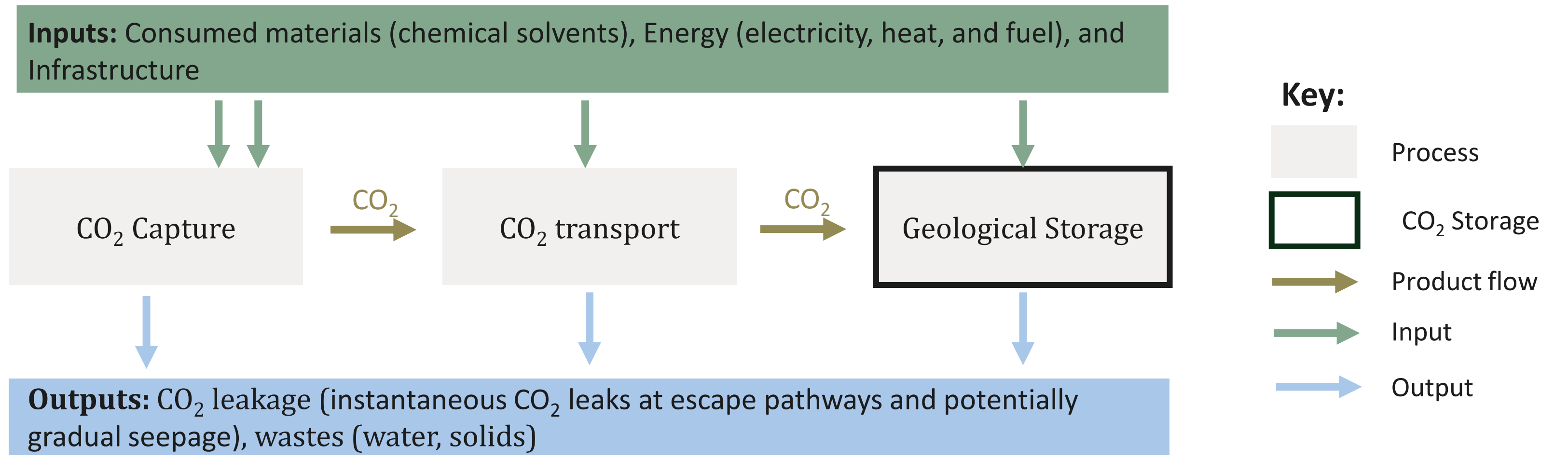
Consideration	Description
Defining the functional unit	It is difficult to define a common functional unit / reference flow (e.g., 1t CO_2 captured and sequestered over X years) due to the different nature of technologies and the fact that carbon removal may be the primary purpose (e.g., DACCS) or a secondary benefit (e.g., biochar). This makes comparison between GGR technologies and LCAs within the same technology difficult.
Definition of system boundaries	Defining the system boundary of the LCA is particularly challenging for technologies where removals are considered an add-on (e.g., BECCS) or a by-product (e.g., Biochar). This can lead to very wide system boundaries. Some processes may also cross the boundaries of the Technosphere and relate to modifying natural processes (e.g., enhanced weathering, seawater removals), thus material/energy flows are not fully in control of economic operators.
Lack of literature	LCA databases may be short of complete data sets (background data). This may lead to the use of proxies, assumptions or internal (non-peer reviewed) data and a lack of robustness and reliability. Foreground data could be provided by technology developers, but as operational projects are currently limited, the data may be primarily theoretical. The temporal and spatial aspects of the data are also important. Carbon sequestration/leakages require modelling/monitoring over long periods. If the data doesn't exist, this will result in a reliance on carbon flow modelling which can be complex. Data in LCA databases may also be restricted to certain geographical locations.
Multifunctionality	Several GGR technologies have multiple functions in addition to removal of GHGs. This raises methodological questions about how the resulting GGR benefits are allocated to different products and systems. For example, biochar is a by-product of pyrolysis of biomass leading to fuel production. Does the fuel also get credited for some of the GGR benefits? Alternatively, when using carbonated building elements, is the building credited for greenhouse gas removals or the technology from which carbon is captured?
Inclusion of infrastructure emissions	Some LCAs include the lifecycle emissions of the permanent materials used to construct GGR infrastructure (such as concrete and steel) and any emissions associated with infrastructure use and replacement (fuel, construction, etc). Although methodological uncertainty can be quite low (and in some process impacts may be negligible), key LCA considerations for infrastructure-related impacts can be: lifetime of infrastructure and decommissioning impacts (including treatment of potential reuse and recycling of equipment/infrastructure), division of emissions associated with shared infrastructure and treatment of reuse of existing infrastructure (e.g. pipelines, offshore injection platforms), system boundary conditions if geological storage is operated and monitored by 3rd parties, and frequency of replacement due to degradation (i.e., corrosion).
Attributional vs consequential LCA methodologies*	Attributional LCA methodologies are more adapted for certain technologies (e.g., DACCS, BECCS), whilst consequential is best suited for others (e.g., biochar, carbonated building elements). Therefore, the overall comparability of GGR technologies and methodological consistency is difficult.

* An attributional LCA inventories all inputs/outputs to the process leading to the desired product/service and "attributes" an environmental impact (e.g., GHG emissions) to each of them; the life-cycle impacts of the product/service results from the sum of input/output impact scores. In a consequential LCA, the impact of one additional unit of product or service is based on the consequence it has over the broader economic system. As an example, an attributional LCA will allocate a share of the GHG emissions of biomass pyrolysis to biochar and pyrolysis oil based on their respective energy content. In a consequential approach, the avoided impact of producing the fossil fuel that pyrolysis oil will eventually replace is credited to the biochar. [Link]

Technology overview and system diagram

DACCS

- Direct Air Capture (DAC) uses chemicals to capture CO_2 from ambient air, which alongside CO2 transport and injection at geological storage sites is referred to as Direct Air Carbon Capture and Storage (DACCS).
- **CO2 capture** from ambient air is divided into various sub-technologies based on capture chemicals/process used. One of the main differentiators between DACCS technologies lies with the nature of solvent (solid or liquid); technologies are usually referred to as solid and liquid DACCS. These different techniques require specific material inputs and energy demands, in the form of electricity and/or heat, but can be generalised in this analysis since MRV methodologies are able to treat all the major DACCS technologies in the same way.
- Innovation in the DACCS sector focuses predominantly on improved capture chemicals, increased energy efficiency and developing processes that can use lower carbon energy sources, such as plants capable of running on electricity only, low grade waste heat, hydrogen, etc.
- **CO2 transport** can be achieved using both pipelines and mobility (tube trailer or shipping) options. The relative economic advantages of these options are determined by the plant location and capacity.
- **Geological storage** refers to the long-term storage of CO2 in geological reservoir formations or through chemical reaction with subsurface rock formations. CO2 can also be utilised in numerous products that offer varying durability of storage depending on their use. In general, CO2 utilisation (CCU) does not lead to long term GGR and is therefore deprioritised for this project.



Summary of existing LCA emissions calculations

- **LCA literature shows that 50 – 150 kgCO_2e are emitted per tCO_2 captured for DACCS with renewable energy supply.** However, results from 30 – 900 kgCO_2e/tCO_2 captured are possible dependant principally on the energy supply used for the atmospheric CO_2 capture process.
- LCA literature for DACCS often distinguishes between solid sorbent and liquid solvent technologies as shown in the table.
- The literature highlights the importance of the source of energy (electricity and/or heat) used in the capture stage as the dominant factor in determining lifecycle emissions2,3,4,6.
- As a result, most papers propose distinct scenarios for energy supply to compare different DACCS configurations. Depending on the energy source used LCAs can result in lifecycle carbon removal efficiencies in the range of 9% to 97%4. Most LCAs assuming utilisation of decarbonised energy sources result in carbon removal efficiencies of approximately 80-95%.
- Other important lifecycle processes highlighted in the LCA literature3,5 are the construction of the DAC plant infrastructure (1%), the adsorbent/ absorbent production (2-3%), and CO_2 transport and storage (~5%) .
- DACCS LCAs show a strong carbon removal efficiency potential yet this can be at the cost of producing other environmental burdens due to increased energy consumption. This raises questions about the environmental trade-offs (such as increased land use for solar farms or additional mining activity for materials used in DAC infrastructure) associated with removing CO_2 from the atmosphere via DACCS.

Reference	Liquid DACCS - kgCO_2e emitted / tCO_2 captured	Solid DACCS - kgCO_2e emitted / tCO_2 captured	Energy Supply
[1] de Jonge et al., 2019	-	380	Grid electricity; natural gas for heat
	-	80	Solar and heat recovery
[2] Singh and Sharston, 2020	700	560	Natural gas for heat; US grid for electricity
	150	-	Natural gas and regeneration for heat; solar PV for electricity
	-	150	Waste incineration for heat; solar PV for electricity
[3] Deutz and Bardow, 2021	-	150	Municipal waste incineration
	-	70	Geothermal energy
[4] Terlouw et al., 2021	-	(30-910)	Varied
[5] Chiquier et al., 2022	200	240	Current UK energy system (electricity and natural gas)
	0 – 80		Late century decarbonised energy system

[1] – LINK; [2] – LINK; [3] – LINK; [4] – LINK; [5] – LINK;

Supply chain and LCA considerations (1/2)

DACCS

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
CO2 Capture	Energy inputs	Emissions associated with the energy inputs to the DACCS facility, both electricity and heat where relevant, such as that used for air fans, solvent pumps, and regeneration/ desorption heating. Use of renewable electricity may increase GHG emissions of the wider electricity supply system if renewable electricity supply does not match DACCS demand in terms of time or geography.	• Ensuring that fluctuating electricity consumption is geographically and temporally aligned with electricity generation. In the case of grid electricity this should include consideration of the inconsistent carbon intensity of the grid • Wider energy system impacts of new supply and demand including considerations of key differences depending on operational philosophy and procurement strategy (baseload, avoided curtailment, PPAs, private wire etc) • Upstream impacts of energy generation, e.g. land use change (direct/indirect), mineral requirements • Carbon intensity of waste heat utilisation, and emissions factor associated to its recycling in the DACCS process • DACCS publications often lack full transparency on the CO2 capture stage due to the competitive, nascent technological market	**Uncertainty:** **High** **Impact:** **Medium**
	Material inputs	Emissions associated with the consumed materials used in the process (liquid solvents or more complex novel chemical solid adsorbents).	• As an emerging and proprietary technology, with minimal process transparency, LCA datasets on (novel) chemicals remain incomplete on key data, such as consumption rate, degradation and lifetime • Quantification of emissions associated with waste product handling and potential recycling of key chemical components	**Uncertainty:** **Medium**
	Uncaptured emissions	Uncaptured carbon losses compared to maximum system capabilities due to downtime, low capture rates etc.	• Uncertain maintenance schedules and reliability issues may influence system up-time • Uncertain capture rates of novel and innovative technological solutions, often only theoretical or optimal estimates available • Crediting of removals between point of capture and point of storage	**Uncertainty:** **Low**

* Indicative uncertainty impact ratings are only provided for components with “high” uncertainty ratings.

Supply chain and LCA considerations (2/2)

DACCS

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
CO2 Transport	Energy inputs	The emissions associated with the energy inputs to the CO_2 transport type. For pipeline solutions this will be electricity for compression and pumping and for trucking and shipping solutions this will be fuel consumption.	• Ability to assess different transportation methods, and combinations of methods • Uncertainty around exact vehicle mileage and the inclusion of return trips	**Uncertainty: Low**
	Leakage	Leakage of carbon during the transport process.	• Consistent assessment of leakage in different transport types, e.g. trucking vs pipeline	**Uncertainty: Medium**
Geological Storage	Energy inputs	The emissions associated with electricity inputs for geological storage. This will include cooling, compression and injection processes.	• A cradle-to-grave LCA system boundary is not always fully implemented, to include downstream injection, (re)compression, and transportation of CO_2.	**Uncertainty: Low**
	Leakage	Leakage of carbon during injection and later from the geological storage site.	• Long term storage over decades/centuries with the potential for gradual leakage requires complex calculation of the overall long-term impact of GHG removal • Rate of various trapping mechanisms (stratigraphic, residual, solution, mineral) • Movement of injected CO_2 plume within storage reservoir • Crediting of removals between point of capture and point of storage	**Uncertainty: Medium**
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations	**Uncertainty: Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Identified options for direct/indirect measurement of inputs and outputs

DACCS

Process	Component	Parameter	Measurement Methods	
CO2 Capture	Energy inputs	Energy consumption profile	Electricity meter, or heat consumed based on flowrate and temperature	D
		Carbon intensity profile of energy supply	Emission factors for electricity and/or heat/steam. Public datasets are often available for grid electricity mixes but will not be available in all countries/jurisdictions. Time correlated data is less common.	I D
		Impact on the wider energy system of additional electricity demand	Energy system modelling of full grid network to realise the impact of additional demand on supply sources	M
	Material inputs	Volume of materials consumed	Volumes consumed, determined for example through receipts for purchased materials	I
		Carbon intensity of consumable materials	Emission factors of chemical inputs	D
	Leakage	CO2 captured	Air flow and CO2 concentrations at the inlet and outlet of the capture unit Air flow and process capture efficiency	D I
CO2 Transport	Energy inputs	Electricity/fuel consumption	Measurement of electricity consumed using an electricity meter Fuel efficiency and distance travelled	D I
		Carbon intensity of electricity/fuel	Emission factors for each electricity/fuel type	I
	Leakage	CO2 leakage	Volumetric flowmeter before and after transport Estimation based on transport specification and distance	D I

Key for measurement method:

- M **Reliant on modelling** – Calculation of parameter is dependent on modelling with limited ability to verify the parameter using field measurements
- I **Indirect measurement** – Parameter is measured using a proxy and a limited number of straightforward calculations
- D **Direct measurement** – Parameter is measured directly and therefore with minimal uncertainty

Identified options for direct/indirect measurement of inputs and outputs

DACCS

Process	Component	Parameter	Measurement Methods	
Geological Storage	Energy inputs	Energy consumption	Measurement of electricity consumed using an electricity meter	D
		Carbon Intensity of electricity supply	Emission factors of energy generation and connection	I
	Leakage	CO_2 volume injected	Volumetric flowmeter at injection	D
		CO_2 leakage	Site monitoring and geological/geochemical modelling. Monitoring methodology will depend on storage typology, e.g. for mineralisation it would consist of subsurface sampling.	M
Full chain	Infrastructure	Volume of materials used	Volumes used in construction, determined for example through technical design drawings or receipts for purchased materials	D
		Carbon intensity of construction materials	Cradle to grave LCA assessment of construction materials	I

Key for measurement method:

- M **Reliant on modelling** – Calculation of parameter is dependent on modelling with limited ability to verify the parameter using field measurements
- I **Indirect measurement** – Parameter is measured using a proxy and a limited number of straightforward calculations
- D **Direct measurement** – Parameter is measured directly and therefore with minimal uncertainty

Key uncertainties (1/2)

DACCS

Process	Uncertainty Type	Description	GGR Standard Questions
CO2 Capture	Methodology: Energy Input	The energy input to the capture process is the key component of the total GHG removal efficiency of DACCS[1]. One challenge is the ability to effectively account for the GHG emissions associated with waste heat utilisation. Quantifying the impact of additional electricity demand for new DACCS plants on the total energy system requires complex system modelling. The impact will be region specific and depend greatly on the energy procurement strategy used by the DACCS facility. This could include utilisation of time-dependent carbon intensities for flexible grid consumption and the assessment of correlation between electricity demand and generation.	• What does the standard require to measure and ensure temporal correlation of electricity consumption and dedicated generation? • Does the system boundary in the standard include an assessment of electricity supply impacts of the wider energy grid, or apply a generalised adjustment to account for this issue? • How does the standard ensure conservative outcomes in employing complex modelling procedures? • How does the standard assess the baseline counterfactual given uncertainty in rapidly evolving grid system? • How does the standard address the potential to utilise waste heat? • Does the standard include provisions for assessing environmental impacts of additional energy generation capacity (e.g. land use change, mineral extraction)?
CO2 Transport and Storage	Methodology: Energy Input	Energy demands for different CO_2 transport types are provided by different sources; electricity for pipelines and fuel consumption for shipping or trucking. Different CO_2 storage mechanisms will also require unique energy inputs. The scope of assessment for different transport and storage mechanisms must be comprehensive and internally consistent to ensure accurate and fair quantification of GHG removals.	• How does the standard provide flexibility for projects using different CO_2 transport and storage types? • How does the standard account for the potential to use multiple CO_2 transport types within the same project (e.g. shipping to a pipeline and storage network overseas)?

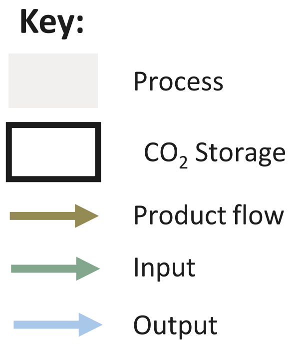
Key uncertainties (2/2)

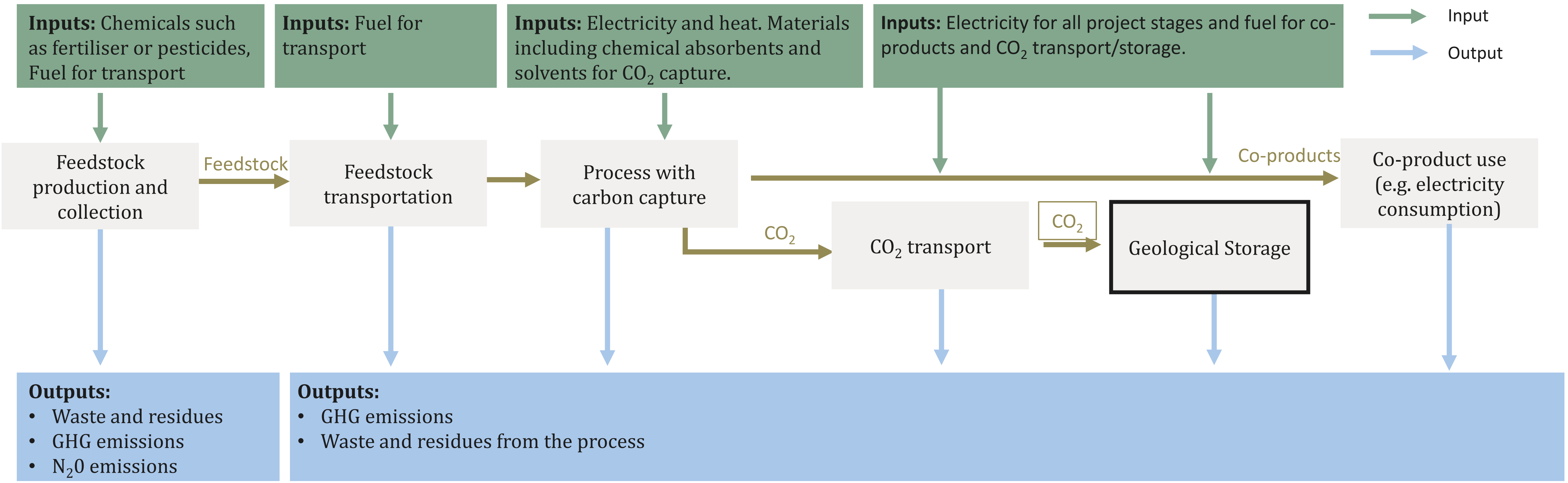
DACCS

Process	Uncertainty Type	Description	GGR Standard Questions
Geological Storage	Measurement: CO_2 migration, trapping and leakage	• Leakage from a storage reservoir can be divided into CO2 seepage into the caprock or surrounding reservoirs, or one-off leakage due to the CO2 escape through a leakage pathway (instantaneous leakage). • Seepage rates of 0.001%-0.1% per year, equivalent to a loss of 1% of CO2 to the surface over 1000 years, has been considered acceptable. • Statistical estimates of reasonable worst-case leakage amount from two 'typical' CO2 storage complexes (depleted hydrocarbon field and saline aquifer) have shown a leakage rate of <0.1% of the stored capacity. • Tracking CO2 migration and leakage will be a site-specific endeavour, with best practices being site and project-specific. • Tracking CO2 trapping mechanisms within the reservoir itself is difficult, but can be achieved through a variety of monitoring methods, including seismic surveys, geochemical tracers, and wellbore fibre optic sensing.	• What is the "acceptable leakage rate" of the standard? • Is the standard sufficiently rigorous to ensure modelling approaches are accurate and verifiable through monitoring schemes (frequency/depth of audit, type of measurements)? • What is the required timeline, intermittency, and techniques required in the monitoring routine? • What is the level and frequency of in situ sampling required to validate the predictions of the 3D modelling (i.e., baseline analysis / risk assessment compatibility)? • Does the standard ensure long term monitoring through liability management (e.g., transfer of liability to public body)? • Does the standard recognise any difference between trapping mechanisms (i.e., reduced liability with proven mineralised CO2)?

Bioenergy with carbon capture and storage (BECCS)

- Bioenergy with carbon capture and storage (BECCS) combines the combustion of biomass for energy generation with carbon capture and geological storage. Atmospheric CO2 is removed via photosynthesis and initially stored as biomass. Following collection and processing, the biomass may be used to generate power, heat, hydrogen or other fuels, with the resulting CO2 captured. Alternatively, CCS may be retrofitted to existing industrial processes that use bioenergy such as pulp, paper or bioethanol production.
- The biomass used may be primary biomass (e.g., crops or wood), residues (e.g., cobs, straws, branches, sawdust) or waste (e.g., demolition wood). In the case of a waste feedstock, only the biogenic portion of the feedstock is considered as carbon removal. This portion varies with location and waste source, e.g., this may be 100% for agricultural and forestry waste but 50% for municipal solid waste from a particular region.





Summary of existing BECCS LCA emissions calculations

BECCS

- A selection of LCA results for BECCS are summarised in the table. Overall, these results highlight the project specific nature of BECCS as a GGR removal technology. The origin and type of feedstock used are key sensitivities which will vary with each project. The life cycle CO_2 removal efficiency over a 100 year timeframe is estimated to range between 62.5% and 85.9% as a result of these feedstock differences and land use changes[8].
- The literature reviewed mostly resulted in a net negative value for greenhouse gas emissions. However, depending on the system boundary, some studies suggested net positive emissions. This was largely due to the inclusion of upstream processes such as feedstock production and solvent manufacture[1].
- There was a range of functional units used across the studies, including areas of land, energy output and feedstock input. Along with methodological differences, this makes direct comparison between studies difficult, as can be seen in the far right column of the table.
- The geographical scopes of the studies are included where available. In reference 3, Fajardy and MacDowell highlight the impact of temporality on net removals (i.e. C payback time) and integrate indirect land-use change to calculate GHG savings on a per ha basis. The study suggests that emissions from indirect land use change are the primary determining factor in LCA results, followed by direct emissions from land use change[3].
- Using waste and residues as feedstock impacts the calculation of ILUC and DLUC emissions. If the feedstock is a waste, upstream feedstock cultivation emissions are not accounted for in LCAs. However, if the feedstock is a residue, a small portion of cultivation emissions are associated with its use, including ILUC and DLUC emissions.

Reference	Configuration	Geographical scope	Global warming potential results
[2] N. Pour, P. A. Webley and P. J. Cook (2018)	BECCS Power	Australia	-0.66 to -1.81 $kgCO_2eq$ per kWh electricity
[3] M. Fajardy and N. Mac Dowell (2017)	BECCS Power	Brazil, China, Netherlands, India, US	For case studies between 31 and -1124 tCO_2eq per ha land
[4] M. Carpentireri, A. Corti, L. Lombardi	BECCS Power	Global	-0.165 $kgCO_2eq$ per MJ of power
[5] C.M. Beal, I. Archibold, M.E. Huntley et al (2018)	BECCS with algae production	Global	-5210 $kgCO_2eq$ per tonne of algae produced
[6] C. Antonini, K. Treyer, A. Streb, et al. (2020)	BECCS Hydrogen	Central Europe	- 125 gCO_2eq per MJ of hydrogen for biomethane as a feedstock
[7] N. Pour, P.A. Webley, P.J. Cook	EfW BECCS	Australia	-0.7 $kgCO_2eq$ per kg of wet MSW incinerated

[1] – LINK [2] – LINK [3] – LINK [4] – LINK [5] – LINK [6] – LINK [7] – LINK [8] – LINK

BECCS supply chain and LCA considerations (1/3)

BECCS

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Feedstock production and collection	Energy and material inputs	The chemicals and fuel used in agricultural processes for biomass cultivation. For example, pesticide or fertiliser used on the fields and fuel consumed by agricultural machinery	• There may be a temporal aspect to use of chemicals and machinery activity in feedstock production. For example, more fuel will be consumed during sowing or harvesting periods of the year.	**Uncertainty:** **Low**
	Field emissions	Crop cultivation and/or forestry operations may lead to changes in the soil organic carbon (SOC) content and increased nitrous oxide emissions.	• Assessing SOC and N_2O emissions require complex modelling and is very dependent on soil type, climate and agricultural practices.	**Uncertainty:** **Medium**
	Direct land use change emissions (DLUC)	A reduction or increase in net greenhouse gas emissions from the change in land use to support feedstock production.	• DLUC emissions are highly dependent on where the feedstock is being produced and the counterfactual case. • When using forestry biomass, a "Carbon Payback Time" exists, i.e. the time a forest would take (through tree growth) to offset the initial C loss from logging.	**Uncertainty:** **Medium**
	Indirect land use change emissions (ILUC)	Using agricultural land for BECCS feedstock production may displace crops for food and feed purposes. This could lead to other land use changes to meet food and feed crop demand (e.g. forest turned into agricultural land)	• ILUC emissions depend on the overall food and feed crop market, as well as the types of land that may be converted for agricultural purposes as an indirect result of the feedstock production. ILUC emissions are difficult to quantify with certainty; factors are typically applied to LCAs.	**Uncertainty:** **High** **Impact:** **High**
	Counterfactual	The change in emissions or sequestration relative to the counterfactual scenario. For example, using manure as a feedstock .	• Assessing alternative fates and defining the counterfactual scenario is a key consideration in LCAs. It may be dependent on location and temporality.	**Uncertainty:** **High** **Impact:** **High**
	Residues	Biomass cultivation produces residues such as straws, leaves, branches, barks, cobs, etc.	• A share of the emissions from feedstock production/collection can be assigned to certain types of agricultural/forestry residues, based on their energy/economic value.	**Uncertainty:** **Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

BECCS supply chain and LCA considerations (2/3)

BECCS

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Process with carbon capture	Energy inputs	Electricity and heat needed for the process (e.g. bioethanol production, hydrogen production via gasification) and for carbon capture. Fuel used for feedstock transportation.	• Energy inputs will vary with the specific BECCS configuration and process. For example, inputs will differ between gasification and pyrolysis-based processes • Carbon intensity of residual heat utilisation, and division between primary and secondary functions	**Uncertainty: Low**
	Material inputs	Embodied emissions in the consumed materials used in the process (capture chemicals).	• Incomplete datasets for LCA on chemicals, such as degradation and lifetime • Quantification of emissions associated with waste product handling and potential recycling of key chemical components	**Uncertainty: Low**
CO2 Transport	Energy inputs	The emissions associated with the energy inputs to the CO_2 transport type. For pipeline solutions this will be electricity for compression and pumping and for trucking and shipping solutions this will be fuel consumption.	• Ability to assess different transportation methods, and combinations of methods • Uncertainty around exact vehicle mileage and the inclusion of return trips	**Uncertainty: Low**
	Leakage	Leakage of carbon during the transport process.	• Consistent assessment of leakage in different transport types, e.g. trucking vs pipeline	**Uncertainty: Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

BECCS supply chain and LCA considerations (3/3)

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Geological Storage	Energy inputs	The emissions associated with electricity inputs for geological storage. This will include cooling, compression and injection processes.	• A cradle-to-grave LCA approach is required, but not always fully implemented, to include downstream considerations such as emissions originating from the injection, (re)compression, and transportation of CO_2.	**Uncertainty:** **Low**
	Leakage	Leakage of carbon during injection and later from the geological storage site.	• Long term storage over decades/centuries with the potential for gradual leakage requires complex calculation of the overall long-term impact of GHG removal • Rate of various trapping mechanisms (stratigraphic, residual, solution, mineral) • Movement of injected CO_2 plume within storage reservoir • Crediting of removals between point of capture and point of storage	**Uncertainty:** **Medium**
Co-product use	Co-products	Other co-products from the process and their use. In the case of BECCS, this could be power, heat, hydrogen, pulp, or bioethanol among others.	• Multifunctionality and allocation method– See general LCA considerations • System boundaries: Some analyses include the avoided emissions from using the co-products to displace fossil fuels. However, sometimes these co-products are not always used (such as residual heat) whilst in other cases, they are the primary products (such as electricity). See general LCA considerations also.	**Uncertainty:** **Medium**
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations	**Uncertainty:** **Medium**

* Indicative uncertainty impact ratings are only provided for components with “high” uncertainty ratings.

Identified options for direct/indirect measurement of inputs and outputs for BECCS (1/2)

BECCS

Process	Component	Parameter	Measurement Methods	
Feedstock production	Energy and material inputs	Quantity of chemicals and fuel	Measurement of chemicals used (e.g. pesticide, fertiliser) and fuel consumed (e.g. for sowing and harvesting)	D
		Greenhouse gas intensity of chemicals and fuel	Either generic inputs Project-specific LCA of chemicals	M I
	Field emissions	Nitrous oxide emissions	Flux chambers may be used on sample areas of the field	I
		Soil carbon changes	Soil samples may be collected and tested for carbon content throughout the year.	I
	DLUC, ILUC & counterfactual case	Relative change in site sequestration and emissions	Project-specific LCA for feedstock used (non-generic inputs) Carbon flow modelling, incl. C payback time. ILUC models	I M M
Process with carbon capture	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
		Carbon intensity of energy supply	Direct project data or literature data on energy generation and connection	I
	Material inputs	Volume of materials consumed	Volumes consumed, determined for example through receipts for purchased materials	D
		Carbon intensity of consumable materials	Cradle to grave LCA assessment of chemical inputs	I
	Leakage	CO2 captured	Air flow and CO2 concentrations at the inlet and outlet of the capture unit Air flow and process capture efficiency	D I

Key for measurement method:

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Identified options for direct/indirect measurement of inputs and outputs for BECCS (2/2)

BECCS

Process	Component	Parameter	Measurement Methods	
CO_2 Transport	Energy inputs	Electricity/Fuel consumption	Measurement of electricity consumed using an electricity meter Fuel efficiency and distance travelled	D I
		Carbon intensity of electricity/fuel	Cradle to grave LCA of electricity/fuel type	I
	Leakage	CO_2 leakage	Volumetric flowmeter before and after transport.	D
Geological Storage	Energy inputs	Energy consumption	Measurement of electricity consumed using an electricity meter	I
		Carbon Intensity of electricity supply	Cradle to grave LCA of energy generation and connection	I
	Leakage	CO_2 volume injected	Volumetric flowmeter at injection	D
		CO_2 leakage	Site monitoring and geological/geochemical modelling. Monitoring methodology will depend on storage typology, e.g. for mineralisation it would consist of subsurface sampling.	M
Full chain	Infrastructure	Volume of materials used	Volumes used in construction, determined for example through technical design drawings or receipts for purchased materials	D
		Carbon intensity of construction materials	Cradle to grave LCA assessment of construction materials	I
Co-product use	Co-products	Quantity of co-products	Volume of co-products produced and/or sold	D
		Counterfactual case (if this approach is used for co-products)	Cradle to grave LCA assessment of counterfactual case	M

Key for measurement method:

- M **Reliant on modelling** – Calculation of parameter is dependent on modelling with limited ability to verify the parameter using field measurements
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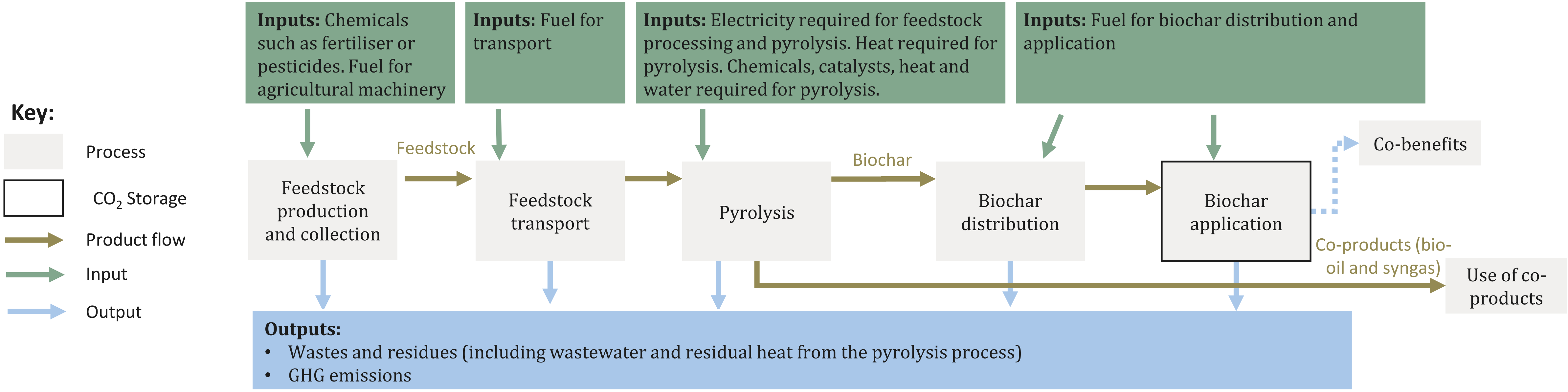
BECCS summary: Key uncertainties

Process	Uncertainty Type	Description	GGR Standard Questions
Feedstock production	Methodology: All feedstock components	Greenhouse gas emissions associated with the feedstock are highly project dependent and are influenced by the feedstock type, location and climate among other factors. This is not always accounted for in LCAs, despite some studies showing it can be the difference between net positive or negative greenhouse gas emissions, particularly in the relation to direct and indirect land use change emissions[1].	• To what extent does the standard allow the use of default values for LCA calculations? Are project specific values required? • Is the temporality of GHG emissions (E.g. C payback time) covered? • Is ILUC covered?
Feedstock production	Methodology: Material inputs	The inclusion of feedstock production processes and inputs in LCA literature depends on the feedstock type, e.g. primary biomass, residues or waste	• How does the standard define waste and residues? • Are waste, residues and primary biomass treated differently under the standard and to what extent?
Feedstock production	Measurement: Field emissions	Measurement methods for soil organic carbon and nitrous oxide emissions may be expensive to implement/verify.	• Does the standard require physical measurements for feedstock production field emissions or is modelling accepted in place?
Co-products	Methodology: Co-products	There are methodological uncertainties in LCA literature between allocation and system expansion approach for co-products.	• How are co-products accounted for under the standard?
CO2 Transport and Geological Storage	Methodology: Energy Input	• See considerations for CO2 transport and storage in DACCS section	• See considerations for CO2 transport and storage in DACCS section
Geological Storage	Measurement: CO_2 migration, trapping and leakage	• See considerations for CO2 storage in DACCS section	• See considerations for CO2 storage in DACCS section
General	Definition of (net) removals	Removals can be understood as the amount of CO2 eventually sequestered, but may as well include process emissions and benefits from substitution of end-products.	• Does the standard include process emissions and/or end-use substitution (E.g. power from BECCS instead of grid power) in the calculation of (net) removals ?

[1] LINK

Biochar

- Biochar is a solid residue resembling charcoal, created through the pyrolysis of organic feedstocks. The feedstocks are comprised of naturally sequestered carbon, up to 70% of which can be stored in the biochar.
- Pyrolysis involves heating the feedstock to high temperatures with no or little oxygen present. The process yields bio-oil, syngas and biochar. The exact product slate, as well as the biochar properties, are determined by the pyrolysis parameters. The higher temperatures used in fast pyrolysis lead to greater biochar stability and permanence of carbon sequestration. However, the lower temperatures and slower heating rates of slow pyrolysis result in higher biochar yield; slow pyrolysis is studied more as a result, as seen on the next slide[1]. Gasification and torrefaction can be used to produce biochar, but pyrolysis is the most prevalent.
- The biochar can then be applied to soil, but it can also be stored in concrete or buried. Application to soil is considered for the remainder of this analysis as this is the most commonly studied use. In a process optimised for biochar yield, is estimated that 54-83% of the carbon content will remain sequestered in the biochar after 100 years. This range depends on soil characteristics such as temperature. However, over a 1000-year timescale, the proportion of carbon that remains sequestered decreases to 6-35%[1,2].
- In addition to storing carbon, applying biochar to soil also stabilises soil organic carbon (SOC) and increases the overall content as a result[2]. This improves soil quality and fertility, bringing co-benefits such as increased crop yield and a reduction in the quantities of fertiliser needed.



 [1] LINK [2] LINK [3] LINK

Summary of existing biochar LCA emissions calculations

Biochar

- Overall, the carbon removal efficiency of biochar is estimated to be between 16% and 38% over a 100 year timescale. Whilst the pyrolysis process is the biggest contributor to the lifecycle emissions, the ILUC and DLUC emissions are the main difference between the most and least efficient scenarios6. For example, using energy-dedicated crops for biochar application to cropland results in greater ILUC and DLUC emissions than using waste feedstocks for biochar application to forests.
- A selection of LCA results for biochar are summarised in the table. A range of feedstocks (including primary biomass) were analysed, although many studies focus on waste and residues such as manure or food waste. Direct and indirect land use change emissions are often not included in these cases7.
- Variations are also seen in terms of:
    - Assumed stability of biochar: this is dependent on the pyrolysis temperature and heating rate, as well as the soil temperature . Best practice for accounting for biochar decomposition in LCAs is an ongoing area of research.
    - Assumed application rate of biochar to soil.
    - Inclusion of soil benefits: Some analyses, such as reference 4, exclude all co-benefits whilst others assume varying levels of reduced fertiliser use, increased crop yield and reduced nitrous oxide emissions6.
    - Biochar yield: The product slate of a pyrolysis facility may be tailored to maximise biochar production or the bio-oil and syngas co-products.

Reference	Feedstock	Pyrolysis temperature	Biochar application rate	Biochar stability	Includes co-product use	Includes co-benefits	Global warming potential results
[1] E.S. Azzi et al. 2019	Woodchips	700 °C slow pyrolysis	0.8 t/ha annually	80%	Yes	Yes	-0.67 kg CO_2-eq/t feedstock (at 21% yield)
[1] E.S. Azzi et al. 2019	Woodchips	700 °C slow pyrolysis	0.8 t/ha annually	80%	Yes	Yes	-1.19 kg CO_2-eq/t feedstock (at 36% yield)
[2] R. Ibarrola et al. 2012	Sewage sludge	Slow pyrolysis	30 t/ha (assumed annually)	68% stable over 100 years	Yes	Yes	-0.79 t CO_2-eq/t feedstock
[2] R. Ibarrola et al. 2012	Cardboard	Slow pyrolysis	30 t/ha (assumed annually)	68% stable over 100 years	Yes	Yes	-0.07 t CO_2-eq/t feedstock
[2] R. Ibarrola et al. 2012	Food waste	Slow pyrolysis	30 t/ha (assumed annually)	68% stable over 100 years	Yes	Yes	-1.07 t CO_2-eq/t feedstock
[3] J.F. Peters et al. 2015	Poplar woodchips	Slow pyrolysis	4.46t/ha annually	90% stable over 100 years	Yes	Some	-1.22 t CO_2 eq/t dry biomass feedstock
[4] H. Thers et al. 2019	Oilseed rape straw	400 °C pyrolysis	1 t/ha	57% after 100 years	Yes	No	171 kg CO2-eq/Mg dry seed compared to reference scenario of 638 kg CO2-eq/Mg dry
[4] H. Thers et al. 2019	Oilseed rape straw	800 °C pyrolysis	1 t/ha	79% after 100 years	Yes	No	111 kg CO2-eq/Mg dry seed compared to reference scenario of 638 kg CO2-eq/Mg dry

[1] – LINK [2] – LINK [3] – LINK [4] – LINK [6] – LINK [7] – LINK

Biochar supply chain and LCA considerations (1/3)

Biochar

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Feedstock production and collection	Energy and material inputs	The chemicals and fuel used in agricultural processes for biomass cultivation. For example, pesticide or fertiliser used on the fields and fuel consumed by agricultural machinery	• There may be a temporal aspect to use of chemicals and machinery activity in feedstock production. For example, more fuel will be consumed during sowing or harvesting periods of the year.	**Uncertainty:** Low
	Field emissions	Crop cultivation and/or forestry operations may lead to changes in the soil organic carbon (SOC) content and increased nitrous oxide emissions.	• Assessing SOC and N_2O emissions require complex modelling and is very dependent on soil type, climate and agricultural practices.	**Uncertainty:** Medium
	Direct land use change emissions (DLUC)	A reduction or increase in net greenhouse gas emissions from the change in land use to support feedstock production.	• DLUC emissions are highly dependent on where the feedstock is being produced and the counterfactual case. • When using forestry biomass, a "Carbon Payback Time" exists, i.e. the time a forest would take (through tree growth) to offset the initial C loss from logging.	**Uncertainty:** Medium
	Indirect land use change emissions (ILUC)	Using agricultural land for biochar feedstock production may displace crops for food and feed purposes. This could lead to other land use changes to meet food and feed crop demand (e.g. forest turned into agricultural land)	• ILUC emissions depend on the overall food and feed crop market, as well as the types of land that may be converted for agricultural purposes as an indirect result of the feedstock production. ILUC emissions are difficult to quantify with certainty; factors are typically applied to LCAs.	**Uncertainty:** High **Impact:** Medium
	Counterfactual	The change in emissions or sequestration relative to the counterfactual scenario. For example, using manure as a feedstock .	• Assessing alternative fates and defining the counterfactual scenario is a key consideration in LCAs. It may be dependent on location and temporality.	**Uncertainty:** High **Impact:** Medium
	Residues	Biomass cultivation produces residues such as straws, leaves, branches, barks, cobs, etc.	• A share of the emissions from feedstock production/collection can be assigned to certain types of agricultural/forestry residues, based on their energy/economic value.	**Uncertainty:** Medium

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Biochar supply chain and LCA considerations (2/3)

Biochar

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Pyrolysis	Energy inputs	Electricity and heat needed for pyrolysis or gasification and any feedstock processing. Fuel consumed associated with transportation of feedstock.		**Uncertainty: Low**
	Energy outputs	Residual heat resulting from the process.	• The residual heat may be reused within the facility	**Uncertainty: Low**
Biochar transport	Energy inputs	Fuel required for biochar distribution and materials for packaging.		**Uncertainty: Low**
Biochar application	Energy inputs	Fuel required for biochar application to soil.	• Allocation if using shared infrastructure. For example, if the biochar is mixed with slurry before application to the soil and solely the slurry would be applied in the counterfactual case	**Uncertainty: Medium**

* Indicative uncertainty impact ratings are only provided for components with “high” uncertainty ratings.

Biochar supply chain and LCA considerations (3/3)

Biochar

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Other impacts of biochar application	Co-benefits	In addition to carbon sequestration, application of biochar to soil may have other benefits such as: • Reduced fertiliser use • Improved crop yield • Reduction in soil nitrous oxide emissions • Stabilisation of heavy metals These benefits are highly dependent on the soil and biochar type - whilst most studies show a significant positive effect, a small number of studies have observed negative impacts on crop yield as a result of biochar application[4].	• LCA studies include co-benefits of biochar to varying degrees. Some include crop yield improvements[1], others improved fertiliser efficiency[2] whilst some do not account for co-benefits at all[3]. Either a system expansion or allocation approach may be taken to account for these co-benefits	**Uncertainty:** **High** **Impact:** **Medium**
Biochar application	GHG emissions	Over time, the biochar decomposes. This results in the leakage of CO_2 emissions from the system.	• Leakage in practice is highly project-specific and dependent on the feedstock, temperature of pyrolysis and soil conditions. Calculations of decomposition are unlikely to be able to use default values to obtain accurate estimates. Research into the stability of biochar is ongoing.	**Uncertainty:** **High** **Impact:** **High**
Co-product use	Co-products	Additional products from the process and their use. In the case of biochar, this includes bio-oil and syngas.	• Multifunctionality and allocation method– See general LCA considerations • System boundaries: Some analyses include the avoided emissions from using bio-oil and syngas to produce low-carbon fuels which displace fossil fuels. See general LCA considerations also.	**Uncertainty:** **High** **Impact:** **High**
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations	**Uncertainty:** **Low**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Identified options for direct/indirect measurement of inputs and outputs for biochar (1/2)

Biochar

Process	Component	Parameters	Measurement Methods	
Feedstock production	Energy and material inputs	Quantity of chemicals and fuel	Measurement of chemicals used (e.g. pesticide, fertiliser) and fuel consumed (e.g. for sowing and harvesting)	D
		Greenhouse gas intensity of chemicals and fuel	Either generic inputs Project-specific LCA of chemicals	M I
	Field emissions	Nitrous oxide emissions	Flux chambers may be used on sample areas of the field	I
		Soil carbon changes	Soil samples may be collected and tested for carbon content throughout the year.	I
	DLUC, ILUC & counterfactual case	Relative change in site sequestration and emissions	Project-specific LCA for feedstock used (non-generic inputs) Carbon flow modelling, incl. C payback time. ILUC models	I M M
Pyrolysis	Energy and material inputs/outputs	Quantity of energy and materials	Measurement of electricity, heat, fuel and chemicals consumed during production and transportation. May include recycling residual heat from pyrolysis process	D
		Greenhouse gas intensity of energy and materials	Either generic inputs or LCA of electricity, heat and fuel consumed	M I

Key for measurement method:

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- D **Direct measurement** – Parameter is measured directly and therefore with minimal uncertainty

Identified options for direct/indirect measurement of inputs and outputs for biochar (2/2)

Biochar

Process	Component	Parameters	Measurement Methods	
Biochar transport & application	Energy and material inputs	Quantity of fuel consumed	Measurement of fuel consumed during transportation and application of biochar	D
		Greenhouse gas intensity of fuel	Either generic inputs or Project-specific LCA of fuel	M I
Other impacts	Co-benefits	Soil benefits estimated through: 1) Fertiliser use 2) Crop yield	1) Measurement of fertiliser used in comparison to a typical site or the project site without biochar 2) Measurement of crop yield comparison to a typical site or the project site before biochar	I I
Biochar decomposition	Leakage	Decomposition rate of biochar	In a lab, biochar decomposition can be measured via carbon-14 labelling. However, conditions are different in the field, where biochar may, for example, be displaced through the soil layers and across ecological compartments. There are also uncertainties regarding whether decomposition is homogenous across the soil. Measurement methods in the field are an ongoing area of research. Soil temperature and the carbon to hydrogen ratio of the biochar can be used to estimate the decomposition rate	I
Co-product use	Co-products	Quantity of co-products	Measure quantity of co-products	D
		Counterfactual	Cradle to grave LCA assessment of counterfactual case	M
Full chain	Infrastructure	Volume of materials used	Volumes used in construction, determined for example through technical design drawings or receipts for purchased materials	D
		Carbon intensity of construction materials	Cradle to grave LCA assessment of construction materials	I

Key for measurement method:

- M **Reliant on modelling** – Calculation of parameter is dependent on modelling with limited ability to verify the parameter using field measurements
- I **Indirect measurement** – Parameter is measured using a proxy and a limited number of straightforward calculations
- D **Direct measurement** – Parameter is measured directly and therefore with minimal uncertainty

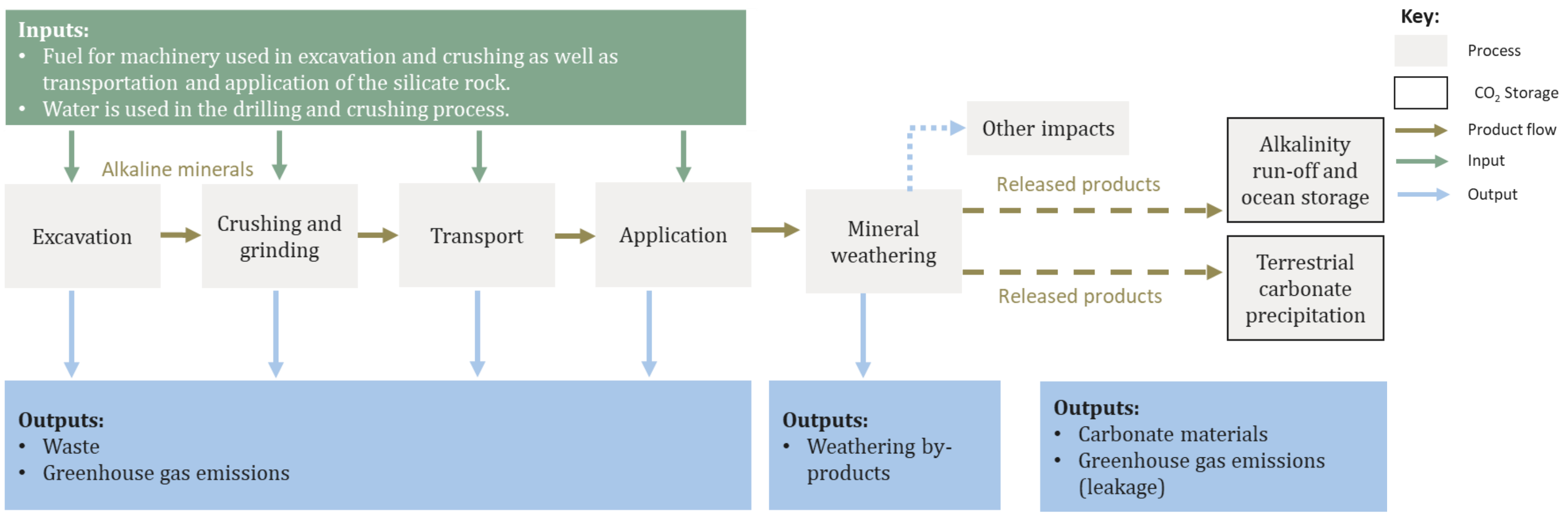
Key uncertainties

Biochar

Process	Key uncertainty	Description and considerations for GGR standards	Key questions for analysis of GGR standards
Feedstock production	Methodology: All feedstock components	• See considerations for biomass feedstocks in BECCS section	• See considerations for biomass feedstocks in BECCS section
Feedstock production	Methodology: Material inputs	• See considerations for biomass feedstocks in BECCS section	• See considerations for biomass feedstocks in BECCS section
Feedstock production	Measurement: Quantifying counterfactual case and indirect land use change emissions	Quantifying these impacts is heavily reliant on carbon flow modelling and difficult to physically measure.	• Does the standard account for the counterfactual use case?
Production process	Methodology: Co-products	There are methodological uncertainties in LCA literature between allocation and system expansion approach for co-products	• How are co-products accounted for under the standard? Are the co-products also credited with some GGR benefit?
Other impacts	Methodology: Co-benefits	Some LCAs include the co-benefits of biochar application, other assessments exclude these benefits. This is largely due to the uncertainty in magnitude and other contributing factors in these co-benefits.	• How are co-benefits accounted for under the standard?
Other impacts	Measurement: Co-benefits	If co-benefits are included, measurement methods for soil organic carbon may be expensive to implement/verify.	• If co-benefits are accounted for, does the standard require physical measurements for co-benefits or is modelling accepted in place?
Biochar decomposition	Measurement: Leakage	Small changes in soil carbon stocks are difficult to directly measure. Biochar decomposition and behaviour in soils are difficult to predict, due to multiple influencing parameters.	• What methods does the standard allow to estimate the decomposition of biochar? • How does the standard account for soil temperature? • How frequently is the carbon to hydrogen ratio of the biochar measured?

Enhanced rock weathering

- Enhanced rock weathering (ERW) involves applying crushed silicate rocks to terrestrial surfaces in order to increases atmospheric CO_2 mineralisation or atmospheric CO_2 drawdown in oceans*. This section focuses on terrestrial applications, but for a full description of ocean processes, see *mineral ocean alkalinity enhancement (OAE)* section.
- In **ERW processes**, the amount and reactive surface area of the silicate rock is increased by applying fine-grained silicate rocks to croplands. The increase in reactive surface area enhances the potential for reactions with atmospheric CO_2 forms and increases net CO_2 removal beyond what would naturally occur otherwise.
- In the **natural weathering process**, atmospheric CO_2 dissolves in rainwater to form carbonic acid. When the carbonic acid comes into contact with silicate rock, the rock "weathers" and releases base cations (such as Ca^{2+}) and carbonate or bicarbonate anions in a process known as mineral dissolution. These released ions then take one of the following paths:
    1. **Weathering path:** The cations released increase the alkalinity of effluent from the site. This effluent ultimately ends up in the ocean and contributes to the ocean's alkalinity and uptake of atmospheric CO_2[1].
    2. **Carbonation path:** Depending on the terrestrial conditions, the cations may also react with atmospheric CO_2 to form carbonate minerals, such as limestone ($CaCO_3$). This mineralisation process is a form of long term storage. However, based on the weathering chemical reactions, a portion of the atmospheric CO2 in the reaction is not mineralised and is instead released back into the atmosphere, meaning that CO2 drawdown in terrestrial applications does not result in a 100% mineralisation rate**.
- The proportion of released anions from the weathering process which result in terrestrial carbon precipitation rather than increased ocean alkalinity is highly project dependent. This proportion is key in determining net greenhouse gas removals.
- The application of alkaline minerals and subsequent weathering effects may cause a variety of additional impacts (both positive and negative) which are dependent on volume of mineral additions and unique terrestrial environment. Examples of these impacts may be the release of nickel and chromium into the environment (suppressing the calcium uptake ability of plants and proving toxic) or providing additional metallic ions (which could be a limiting nutrient) to otherwise nutrient-poor soils.



Summary of existing ERW LCA emissions calculations

ERW

- The CO_2 removal efficiency of ERW systems typically ranges from 63% to 92%, depending on the type of silicate rock type, particle size and geographical scope. Reducing the rock to the desired size and transport of the crushed rock from quarry to application site are both energy intensive processes which can contribute greatly depending on the project set up.
- Whilst smaller particles result in faster weathering, crushing requires more energy and therefore more greenhouse gas emissions to reach smaller sizes. Therefore, a trade-off exits between the required particle size to enhance weathering effect, and the energy required (and subsequent GHG emissions) to obtain such size, which may offset some of the benefits of carbon sequestration.
- The LCA literature is very limited for ERW, compared with other GGR technologies and therefore, additional research would be required to fully understand environmental risks and opportunities, as well as specific GHG accounting methodological questions[5].
- A selection of scientific publications are summarised in the table, including one study looking at application of ERW to coastal zones. Studies looking at sequestration potential but without any LCA relevance are not considered here.

[1] – LINK; [2] – LINK; [3] – LINK; [4] – LINK; [5] – LINK

Reference	Silicate rock type	Particle size	Geographical scope	Global warming potential results	Rate of carbon sequestration
TERRESTRIAL [1] D. Lefebvre, P. Goglio, A. Williams et al. (2019)	Basalt rock	5000 µm	Sao Paulo, Brazil	Enhanced rock weathering and carbonation respectively emit around 75 and 135 kg CO_2eq per tonne of CO_2eq removed	Not specified
TERRESTRIAL [2] J. Cooper, L. Dubey, A. Hawkes (2022)	Olivine	10 µm	USA	~380 kg CO_2eq per tonne of CO_2 removed in the base case	Average of 45 years for 1 tonne of olivine to sequester 1 tonne of CO_2
TERRESTRIAL [3] Chiquier et al. (2022)	Basalt	10 µm	UK	GGR efficiency 92.2% (max sequestration potential 200 kgCO_2 per tonne rock)	Carbonation rates ranging from months to decades
		50 µm		GGR efficiency 97.2% (max sequestration potential 200 kgCO_2 per tonne rock)	
	Dunite	10 µm		GGR efficiency 68.9% (max sequestration potential 900 kgCO_2 per tonne rock)	
		50 µm		GGR efficiency 63.1% (max sequestration potential 900 kgCO_2 per tonne rock)	
COASTAL [4] S. Foteinis, J.S. Campbell, P. Renforth (2023)	Olivine	10 µm	Europe	50.7 kg CO_2eq per tonne of CO_2 removed	~ several months to become net negative
		1 µm		233 kg CO_2eq per tonne of CO_2 removed	~ several months to become net negative
		1000 µm		14.2 kg CO_2eq per tonne of CO_2 removed	5 to 37 years to become net negative

ERW supply chain and LCA considerations (1/2)

ERW

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Excavation	Material inputs	The emissions associated with the water and explosives used in the excavation process as well as the lubricating oil used to operate the machinery	• It is possible to use waste from mines and quarries instead of dedicated excavation. Emissions from this process might then be excluded in an LCA.	**Uncertainty: Medium**
	Energy inputs	Fuel used to operate the machinery	• Emissions associated with fuel combustion	**Uncertainty: Low**
Crushing and grinding	Energy inputs	Electricity used to crush the silicate rock and fuel used for transporting the rock to the crushing facility	• Emissions associated with sourcing and electricity production method	**Uncertainty: Low**
	Material inputs	Water used in the crushing process	• Emissions associated with pumping and treatment (note that the volume of water required for treatment is also a consideration for overall project impact, but is not as impactful within LCA)	**Uncertainty: Low**
Transport	Energy inputs	Fuel used to operate distribution vehicles	• When considering average quarry to field distances, transportation by truck can be the most impacting process on overall system emissions[1].	**Uncertainty: Low**
Application	Energy inputs	Fuel used to operate spreading devices (machinery, planes, etc) for applying the crushed rock to the land.	• Emissions associated with fuel combustion	**Uncertainty: Low**
	Direct land use change (dLUC)	See LCA considerations under BECCS	• See LCA considerations under BECCS	**Uncertainty: Medium**
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations	**Uncertainty: Low**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings. [1] LINK [2] LINK [3] LINK [4] LINK

ERW supply chain and LCA considerations (1/2)

ERW

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Other impacts (including non LCA)	Co-benefits	Studies suggest that enhanced weathering improves crop growth and soil fertility. This could result in reduced fertiliser use, reduced lime application and increased biomass[2].	• Improved crop growth and soil fertility may be addressed through a consequential approach whereby the avoided production and use of fertilisers is credited to the ERW system.	**Uncertainty:** Medium
	Weathering by-products	Metallic cations released from weathering	• Some studies suggest that weathering of olivine may also release nickel and chromium into the environment. This could suppress the calcium uptake ability of plants and prove toxic[4]. However, this doesn't extend to all silicate rocks – basalt, for example, has much lower concentrations of nickel and chromium.	**Uncertainty:** Medium
Terrestrial carbonate precipitation	Leakage and carbonate materials	The proportion of the released terrestrial cations which are transported to the ocean or result in the precipitation of carbonate minerals, as the level of atmospheric CO2 drawdown is different between the two environments.	• The proportion of cations which is ultimately transported in the site effluent into oceans remains a large source of uncertainty in research and LCAs[1].	**Uncertainty:** High **Impact:** High
Additional sources of leakage	Leakage: Ocean outgassing	During the transportation of the dissolution products to the ocean, outgassing may occur (see ocean removals) as the products reach surface waters. The large time and spatial scales make this difficult to accurately account for[3].	• These processes resulting in leakage are not accounted for in current LCA literature but have been proposed for inclusion in MRV standards by organisations such as Carbon Plan. As LCA studies on enhanced weathering develop, these downstream processes may be considered to be within the system boundaries. However, this will also be dependent on the timescales considered and the threshold for "permanent" storage. • Separating "natural" weathering processes from those induced through ERW may also prove challenging, as accurately identifying where CO2 has been sequestered or mineralised due to ERW will be critical for assessing net removal potential	**Uncertainty:** High **Impact:** Medium
	Leakage: Ocean storage	Over geological timescales, the dissolved carbon will eventually precipitate. The rates of mineralisation in ocean primary and secondary precipitation may be different than those found in terrestrial environments, making tracking CO_2 mineralisation as a direct or indirect result of ERW challenging.		**Uncertainty:** High **Impact:** Low

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings. [1] LINK [2] LINK [3] LINK

Identified options for direct/indirect measurement of inputs and outputs for ERW (1/2)

ERW

Process	Component	Parameters	Measurement Methods	
Excavation	Energy inputs	Quantity of fuel	Measurement of fuel consumed (e.g. for machinery)	D
		Greenhouse gas intensity of inputs	Emission factors from LCA databases vs project-specific emission factors	M
	Material inputs	Quantity of water and explosives	Measurement of water and explosives used	D
		Greenhouse gas intensity of inputs	Emission factors from LCA databases vs project-specific emission factors	M
Crushing and grinding	Energy inputs	Quantity of electricity or fuel	Measurement of electricity and fuel used and calculations on associated GHG emissions	D
		Greenhouse gas intensity of electricity	Either generic inputs or Project-specific LCA of chemicals	M I
	Material inputs	Quantity of water	Measurement of water used	D
		Greenhouse gas intensity of inputs	Either DEFAULT inputs or Project-specific LCA of chemicals	M I
Transport and Application	Material inputs	Quantity of fuel	Measurement of fuel consumed	D
		Greenhouse gas intensity of fuel	Emission factors from LCA databases vs project-specific emission factors	M

Key for measurement method:

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Identified options for direct/indirect measurement of inputs and outputs for ERW (2/2)

ERW

For measuring mineral weathering, there are two main approaches; observing the weathering of the applied silicate rock or monitoring the alkalinity of the site effluent. The parameters needed for each approach to gain a full picture of carbon sequestration are explored under each method. For the observation of weathering approach, it is important to measure the amount of weathering caused by non-carbonic acid influences, as this should not be included in net GGR calculations.

Process	Component	Parameters	Measurement Methods	
Mineral weathering	Approach 1: Weathering of applied silicate rock	Mineral weathering rate (i.e., the production of ions which may contribute to either terrestrial or ocean CO_2 drawdowns)	Elemental analysis (samples) Tracking changes in concentration of tracers (such as tracer isotopes) components in samples[3]	I I
		Proportion of weathering from non-carbonic acid (and therefore not contributing to carbon storage)	Project-specific modelling based on mineral chemical composition and project environment (i.e., chemical reactions occurring in various terrestrial environments based on the availability of different minerals, chemicals and compounds)[3].	M
		Formation of secondary minerals which may counteract increased alkalinity (such as clay)	Project-specific modelling or soil mineralogy techniques may be used such as x-ray diffraction[3].	M I
	Approach 2: Monitoring effluent from site	Alkalinity (i.e., cations such as Ca^{2+} and Mg^{2+}) which are released from weathering effects into the effluent from site which may lead to oceans and facilitate further CO_2 drawdown	Monitoring any two of the following in the site effluent[3]: • pH • Total alkalinity • Partial pressure of CO_2 • Dissolved inorganic carbon (DIC)	D
Additional sources of leakage	Potential leakage resulting from mineral effluent into oceans and subsequent ocean reactions other than increasing CO2 drawdown	See ocean removals section	See ocean removals section	M I D

ERW summary: Key uncertainties

ERW

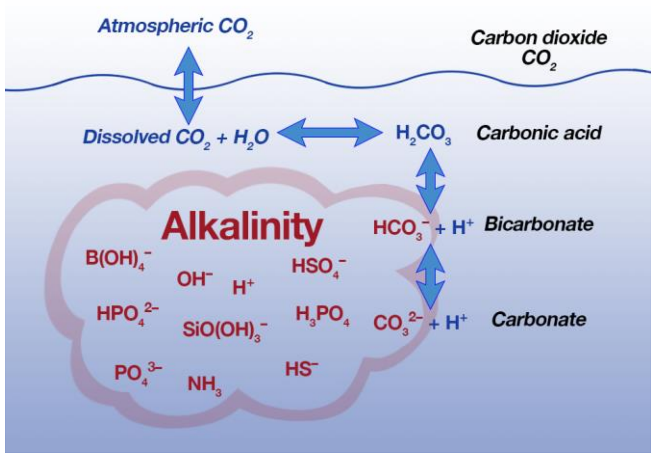
Process	Key uncertainty	Description and considerations for GGR standards	Key questions for analysis of GGR standards
Weathering	Measurement: Proportion of bicarbonate ions from weathering process contributing to ocean alkalinity	The proportion of released ions from the weathering process which result in increased ocean alkalinity is highly project dependent. This proportion is key in determining net greenhouse gas removals. Some measurement methods, such as direct observation of rock weathering, do not measure this proportion directly. In this case, it may need to be accounted for with modelling or other methods (see previous section).	• How does the standard account for the difference in sequestration? • Are certain measurement methods specified? • Are effects not leading to carbon sequestration accounted for in the methodology? For example, such as secondary mineral formation or non-carbonic acid weathering.
Weathering	Measurement: Proportion of bicarbonate ions from weathering process contributing to carbonate precipitation	The proportion of released ions from the weathering process which result in terrestrial carbon precipitation is highly project dependent. This proportion is key in determining net greenhouse gas removals. Neither direct observation of rock weathering nor measuring increased alkalinity, directly account for this and so may need to be accounted for with modelling or other methods (see previous section).	• How does the standard account for the difference in sequestration? • Are certain measurement methods specified? • Are effects not leading to carbon sequestration accounted for in the methodology? For example, such as secondary mineral formation or non-carbonic acid weathering,.
Additional sources of leakage	Method: Leakage via outgassing from effluent	Outgassing from effluent was not always accounted for in reviewed LCA literature but was proposed by organisations such as Carbon Plan.	• Is outgassing as a result of increased effluent alkalinity accounted for in the standard?
Full chain	Method: Counterfactual	As this greenhouse gas removal method is an enhanced version of a natural process, MRV methods rely on establishing what has changed relative to the counterfactual.	See general LCA considerations
Other impacts	Method: Co-benefits	Depending on where the system boundary is drawn, co-benefits may be included in LCAs of ERW systems. This includes increased crop yields and improved soil quality. There is not a clear consensus on the inclusion or exclusion of co-benefits for ERW.	• How are co-benefits accounted for under the standard?

Inorganic chemistry basics of marine GGRs

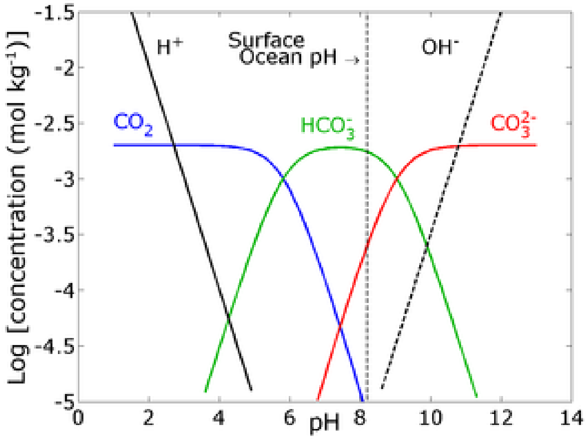
Oceans

- **Context:** Oceans are among the largest natural carbon sinks, holding an estimated 42 times more carbon than the atmosphere and absorbing 30% of previous anthropogenic emissions. This is due to their significant buffering capacity, which neutralises dissolved CO_2 via various dissolved bases – collectively known as total alkalinity (TA).
- **How oceans absorb atmospheric CO_2:** As the surface ocean pH is slightly basic (8.1), atmospheric CO_2 is drawn down into the surface layer to form **carbonic acid (H_2CO_3)**. Based on the equilibrium state of the seawater, the carbonic acid then immediately disassociates into **bicarbonate (HCO_3^-)**. Should the system be basic enough (very rare in most marine systems), then further disassociation into **carbonate (CO_3^{2-})** may occur (see reaction below). The various forms of carbon within seawater (CO_2, H_2CO_3, HCO_3^-, CO_3^{2-}) are collectively known as **dissolved inorganic carbon (DIC)**.
  - $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow H+ CO_3^{2-}$
  - As more atmospheric CO_2 dissolves into the ocean, pH decreases – a process known as ocean acidification. This has negative impacts for calcifiers (molluscs, corals, etc) and other forms of marine life.
- **Engineered (abiotic) marine GGR** projects increase drawdown of atmospheric CO_2 through:
  - Removing CO_2 (or other acids) from captured seawater (acid removal) and/or introducing more alkaline substances to the marine water column (base addition).
  - This results in an increase in the drawdown potential of atmospheric CO_2 into the surface ocean layer in a manner which does not contribute to ocean acidification (as overall equilibrium is maintained).
- **Engineered marine GGR techniques may use the above concepts via:**
  - **Direct Ocean Removals (DOR):** removal of CO_2 from captured seawater via electrochemical or other techniques (thus lowering alkalinity), then re-addition of the higher pH seawater to facilitate atmospheric drawdowns. The captured CO_2 is transferred for long-term underground storage.
  - **Ocean alkalinity enhancement (OAE):** increasing the total relative alkalinity of seawater by capturing seawater and removing acid (i.e., HCl) via electrochemical techniques, or adding alkaline substances to marine outfalls and/or directly to the marine water column.
- All marine GGR projects should expect some degree of **secondary biotic and abiotic impacts** (either positive or negative).
- As most marine GGR projects are still at **early development stages, LCA and other accounting practices are still being actively developed and improved.**

Illustration of how Total Alkalinity acts as the ocean's buffering capacity for dissolved CO2



Bjerrum plot – the chemical form of CO_2 may either be released or trapped in other DIC forms as a function of pH

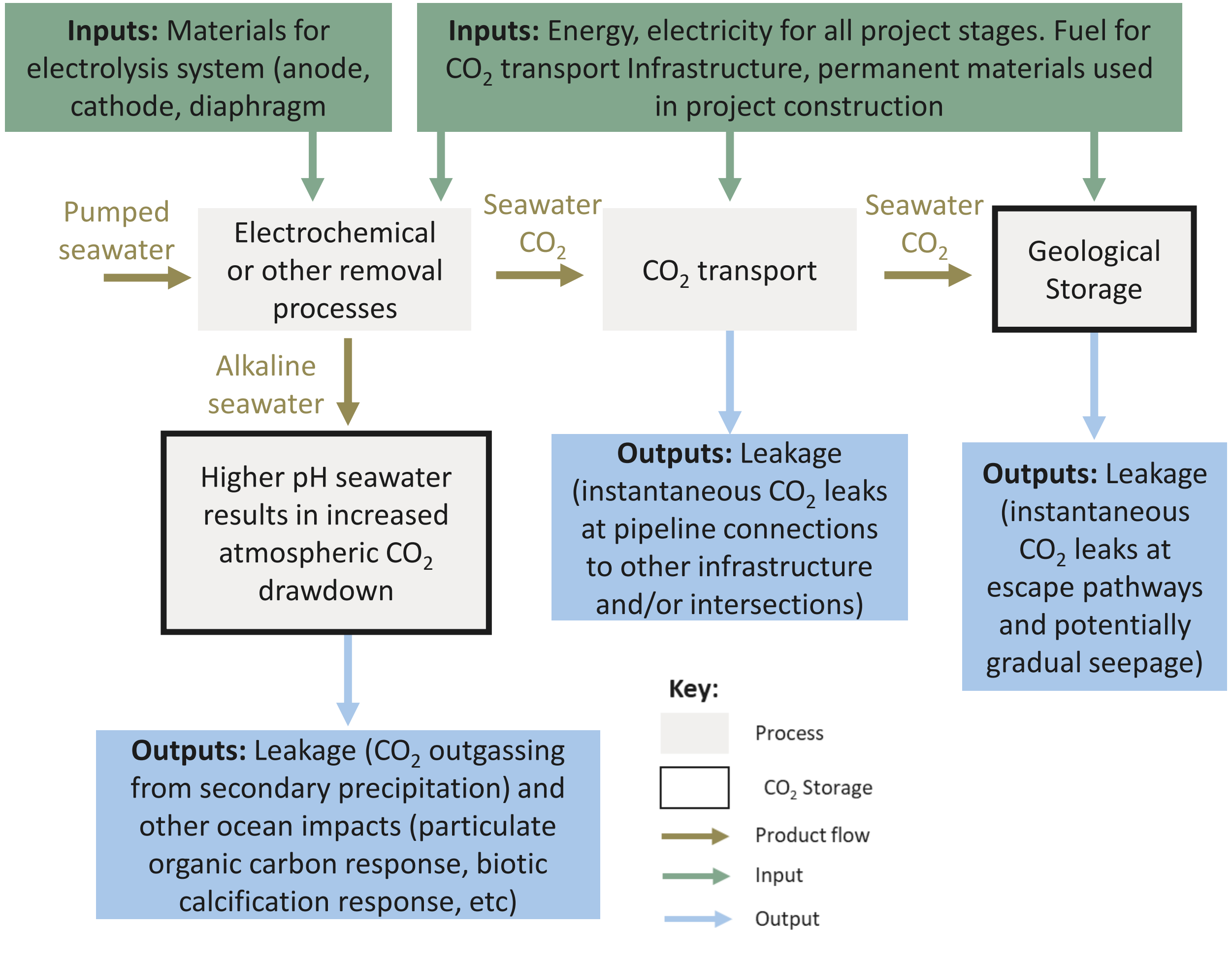


OnCirculation – Link
NASA - Link

*Biotic measures which increase the natural rate of photosynthesising elements (seaweed cultivation, coastal blue carbon, artificial upwelling), are also being developed. However, similar to other nature-based solutions, these may lack CO_2 removal permanence and have been omitted from this report.

Technology Overview and System Diagram – Direct Ocean Removal

- **Direct Ocean Removal (DOR)** works by removing CO_2 from seawater pumped from the surface ocean layer via electrochemical or other techniques, then re-addition of the higher pH seawater to the ocean to facilitate atmospheric CO_2 drawdowns. The captured CO_2 is transported for long-term underground storage*.
- **Step 1:** The process works by removing surface layer seawater from the water column, then subjecting it to a variety of techniques for CO_2 removal:
  - **Electrochemical processes** create streams of acid (H^+) at a system anode and base (OH^-) at a system cathode. There are two different techniques:
    - Acid processes exploit the lower pH conditions around the anode, which moves the equilibrium of the carbonate system in the captured seawater towards CO_2 from HCO_3^-.
    - Base processes exploit high-pH conditions created around the cathode to shift the equilibrium of the carbonate system toward a greater concentration of HCO_3^- and/or CO_3^{2-}, causing carbonate precipitation and an increase in CO_2. Total Alkalinity must be restored before seawater is returned to the ocean in order to facilitate CO_2 drawdown.
  - **Other CO_2 capture processes** are being developed, using a combination of nanofiltration, mineral precipitation, desorption, resin towers, and bipolar membrane electrodialysis.
- **Step 2:** Dissolved CO_2 in the seawater (now in greater concentration due to processes above) is then vented from the solution and transported for geological storage. It is likely that this service would be provided by a **dedicated transport and storage (T&S) service provider.**
- **Step 3**: The now higher pH seawater (due to removal of CO_2) is returned to the ocean to facilitate additional CO_2 drawdown from the atmosphere.
- There are **no developed full chain LCAs for DOR projects**, with several organisations outlining LCA development as critical next funding steps. For example, UK-based developer **SeaCURE** has outlined a target date of late 2024 for an initial LCA.



*CO_2 utilisation may provide an additional revenue opportunity, but unless the utilisation routes result in long-term sequestration of the CO_2 (such as cement building materials), storage permanence would be challenging to guarantee, and GGR would not be achieved.

NASEM, 2021 – Link
Carbon Plan – Link
Climeworks Foundation, 2021 – Link
SeaCURE GGR Phase 1 final report – Link

Supply chain and LCA considerations (1/2)

DOR

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
CO_2 capture from seawater	Energy inputs	The emissions association with the energy inputs to the electrochemical or other capture process, both electricity and heat where relevant.	• Carbon intensity of waste heat utilisation • Impacts from energy generation, e.g. land use change, mineral requirements	**Uncertainty:** **Medium**
	Material inputs	Emissions associated with the consumed materials used in the electrochemical or other capture process (minerals, resin, membranes, etc).	• Quantification of emissions associated with materials production, handling and potential recycling of key chemical components	**Uncertainty:** **Low**
	Leakage	Any difference between the CO_2 removed from seawater and the CO_2 that is measured as a metered input to the storage system.	• Mass of CO_2 evolved from the solution or formed in various precipitates	**Uncertainty:** **Low**
Full chain	Infrastructure	<u>See general LCA considerations</u>	• <u>See general LCA considerations</u>	**Uncertainty:** **Low**
CO_2 Transport	Energy inputs	The emissions associated with the energy inputs to the CO_2 transport type. For pipeline solutions this will be electricity for compression and pumping and for trucking and shipping solutions this will be fuel consumption.	• Ability to assess different transportation methods, and combinations of methods • Uncertainty around exact vehicle mileage and the inclusion of return trips	**Uncertainty:** **Low**
	Leakage	Leakage of carbon during the transport process.	• Consistent assessment of leakage in different transport types (i.e., ship & pipeline)	**Uncertainty:** **Medium**
Geological Storage	Energy inputs	The emissions associated with electricity inputs for geological storage. This will include cooling, compression and injection processes.	• A cradle-to-grave LCA approach is required, but not always fully implemented, to include downstream considerations such as emissions originating from the injection, (re)compression, and transportation of CO_2.	**Uncertainty:** **Low**
	Leakage	Leakage of carbon during injection and later from the geological storage site.	• Long term storage over decades/centuries with the potential for gradual leakage requires complex calculation of the overall long-term impact of GHG removal • Rate of various trapping mechanisms (stratigraphic, residual, solution, mineral) • Movement of injected CO_2 plume within storage reservoir • Crediting of removals between point of capture and point of storage	**Uncertainty:** **Medium**

*Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Supply chain and LCA considerations (2/2)

DOR

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Atmospheric CO_2 drawdown via air-sea gas exchange	-	The carbonate system will seek to re-equilibrate with either an increased drawdown of CO_2 from the atmosphere or a decreased CO_2 outgassing.	• The magnitude of dispersal of DIC-depleted water, as less-concentrated DIC-depleted seawater could be re-equilibrated by other means other than atmospheric CO_2 drawdown • Residence time of DIC-depleted water at the ocean surface, as sunken DIC-depleted seawater will not interact with the air (CO_2 drawdown or reduction in CO_2 outgassing) • The exact timing, area, and rate of both exchange and re-equilibration is still highly uncertain. Current uncertainty may impact 20-50% of removal potential[1], although advances in modelling capabilities suggest this uncertainty could be decreased in the near/mid future.	**Uncertainty:** **High** **Impact:** **High**
Potential impacts from higher pH seawater return to ocean	-	The re-introduction of alkaline seawater to the ocean may result in several processes which will result from lower DIC or will seek to restore the lower DIC to previous equilibrium (other than atmospheric CO_2 drawdowns) via processes such as secondary precipitation and/or biotic calcification.	• Secondary precipitation: The removal of CO_2 from the seawater will cause pH shifts, which may result in abiotic precipitation of other minerals (i.e., brucite, etc). In order to equilibrate with this secondary precipitation, there could be an increase in oceanic dissolved CO_2 turning back into a gas and being released back to the atmosphere (outgassing). While the extent of this process and its magnitude in response to marine DOR is currently unclear, any CO_2 released back into the atmosphere from the oceans as a result of DOR projects must be subtracted from the negative emissions potential of the project. • Biotic calcification: Any changes to ocean DIC caused by DOR projects may increase/decrease the rate of biotic calcification (i.e., shell formation), as shells may form/dissolve in order to absorb or release TA as needed by the water around them. Therefore, reduction in biotic calcification should be considered for net GGR potential. • Similar to air-sea gas exchange, the difficulty in tracking complex secondary aqueous biogeochemistry reactions in real time means there is still a great degree of uncertainty on evaluating secondary impacts. Current uncertainty may impact as high as 5-20% of removal potential*, although advances in modelling capabilities suggest this uncertainty could be decreased in the near/mid future	**Uncertainty:** **High** **Impact:** **Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings. [1] CarbonPlan DOR v1.0 – Link

Identified options for direct/indirect measurement of inputs and outputs (1/2)

DOR

Process	Component	Parameter	Measurement methods	
CO_2 capture from seawater	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
		Carbon Intensity of Energy Supply	Cradle to grave LCA of energy generation and connection, including grid reinforcement infrastructure	I
	Material inputs	Volume of materials consumed	Volumes consumed	D
		Carbon intensity of consumable materials	Cradle to grave LCA assessment of chemical inputs	I
	Infrastructure	Associated emissions	Cradle to grave LCA assessment of construction materials	I
	Leakage	CO_2 captured*	CO_2 removal measured directly as a metered output from the direct ocean removal (DOR) system. Checked for consistency against operational data from the DOR system and characterization of the seawater effluent that is depleted of DIC.	D M
CO_2 Transport	Energy inputs	Electricity/Fuel consumption	Measurement of electricity consumed using onsite metering / Fuel efficiency and distance travelled	D
		Carbon intensity of electricity/fuel	Cradle to grave LCA of electricity/fuel type	I
	Leakage	CO_2 leakage	Volumetric flowmeter before and after transport Direct sensors at key pipeline connections and terminals	I D

Key for measurement method:

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*The quantity of CO_2 directly removed from seawater may not be equal to the quantity of CO_2 stored or the quantity of CO_2 indirectly removed by atmospheric drawdown. Thus, the quantity of CO_2 removed directly from seawater must be clearly quantified and validated as a separate measurement from CO_2 storage or atmospheric CO_2 drawdown.

Identified options for direct/indirect measurement of inputs and outputs (2/2)

DOR

Process	Component	Parameter	Measurement methods	
Geological Storage	Energy inputs	Energy consumption	Measurement of electricity consumed using	D
		Carbon Intensity of electricity supply	Cradle to grave LCA of energy generation and connection	I
	Leakage / fate of CO_2	CO_2 volume injected	Volumetric flowmeter at injection	D
		CO_2 trapping and leakage	3D seismic surveys, downhole pressure/temp readings, tracers, analysis of deep fluid chemistry, sonar bubble stream detection, pulse-testing, water bottom gas sampling, shallow subsurface geochemistry, satellite interferometry / GPS, etc [1].	M D
Atmospheric CO_2 drawdown via air-sea gas exchange	Atmospheric CO_2 (in various DIC forms)	Various DIC forms and associated changes in carbonate chemistry	In-situ measurements can potentially track post-deployment changes in pCO_2, pH, and DIC and deploy water mass tracers to help validate models of plume dispersal and atmospheric CO_2 drawdown	M D
Secondary Impacts from higher pH seawater return to ocean	Secondary precipitation	Formation of secondary precipitates such as $CaCO_3$	Seawater sampling, laboratory experiments and geochemical mass balance modelling	M D
	Biotic calcification	Quantification of biotic calcification	Seawater sampling, laboratory experiments and geochemical mass balance modelling	M D

Key for measurement method:

- M **Reliant on modelling** – Calculation of parameter is dependent on modelling with limited ability to verify the parameter using field measurements
- I **Indirect measurement** – Parameter is measured using a proxy and a limited number of straightforward calculations
- D **Direct measurement** – Parameter is measured directly and therefore with minimal uncertainty

[1] IEAGHG monitoring selection tool – Link;

Key uncertainties

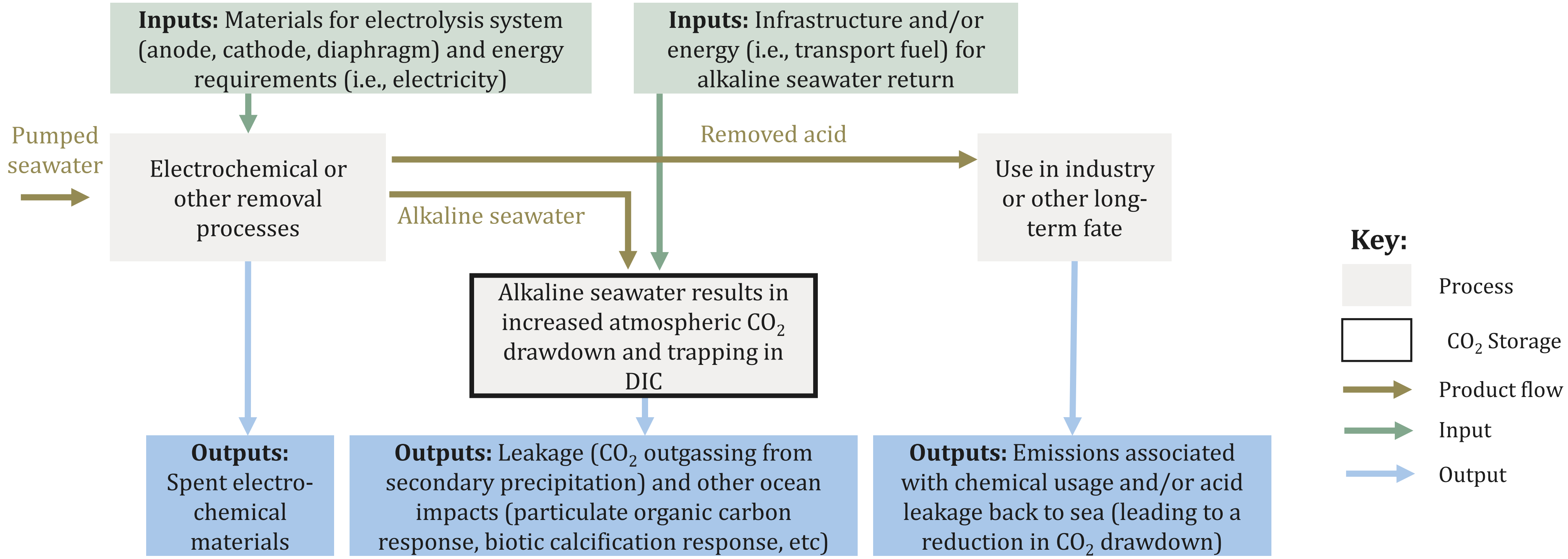
DOR

Process	Uncertainty Type	Description	GGR Standard Questions
Geological Storage	Measurement: CO_2 migration, trapping and leakage	• See key uncertainties for geological storage under DACCS	• See key uncertainties for geological storage under DACCS
Air-sea gas exchange	Measurement: Atmospheric CO_2 (in various DIC forms) and changes in carbonate chemistry	• Quantifying the mass of CO_2 which has been drawn down from the atmosphere as a result of higher pH of returned seawater, relative to the degassed CO_2 returned to atmosphere • The precise dispersal of DIC-depleted seawater in the water column (location, residence time at surface, etc) • Residence time of absorbed atmospheric CO_2 within seawater DIC (i.e., how long is CO_2 "trapped" as bicarbonate before re-aligning with geological carbon cycles such as shell formation, seafloor subduction and recycling, etc)	• What is the modelling method of quantifying the mass of CO_2 which has been absorbed from atmosphere directly as a result of DOR activities? Have these models shown to be both precise and accurate with in situ measurements? • What is the method for tracking the dispersal of DIC-depleted seawater once it is returned to ocean? • Should absorbed atmospheric CO_2 be considered "trapped" if incorporated into DIC?
Secondary precipitation	Measurement: Formation of secondary precipitates such as $CaCO_3$	The removal of CO_2 from the seawater will cause pH shifts, which may result in abiotic precipitation of other minerals (i.e., brucite, etc). In order to equilibrate with this secondary precipitation, there could be an increase in oceanic dissolved CO_2 turning back into a gas and being released back to the atmosphere (outgassing). While the extent of this process and its magnitude in response to marine DOR is currently unclear, any CO_2 released back into the atmosphere from the oceans as a result of DOR projects must be subtracted from the negative emissions potential of the project [1].	• Should the standard measure the level of secondary precipitation as a proxy for CO_2 outgassing, and should this be subtracted from the net GGR potential? • What methods should be acceptable for tracking and quantifying secondary precipitation and/or CO_2 outgassing?
Biotic calcification response	Measurement: Quantification of biotic calcification	Since calcification releases CO_2, any changes to the rate of biotic calcification in response to shifts in pH and dissolved inorganic carbon (DIC) concentrations driven by the direct ocean removal process must be considered. Changes in biotic calcification rates could occur in both coastal and open ocean waters, and at the level of individual calcifiers or calcifier populations. In practice, quantifying the biotic calcification response to carbon-depleted water may pose significant spatial, temporal, and signal-to-noise challenges [1].	• Can the rates of biotic calcification as a response to DOR activities be accurately and precisely tracked in order to be subtracted from the GGR performance?

[1] CarbonPlan DOR v1.0 – Link

Technology Overview and System Diagram – Ocean alkalinity enhancements (1/2)

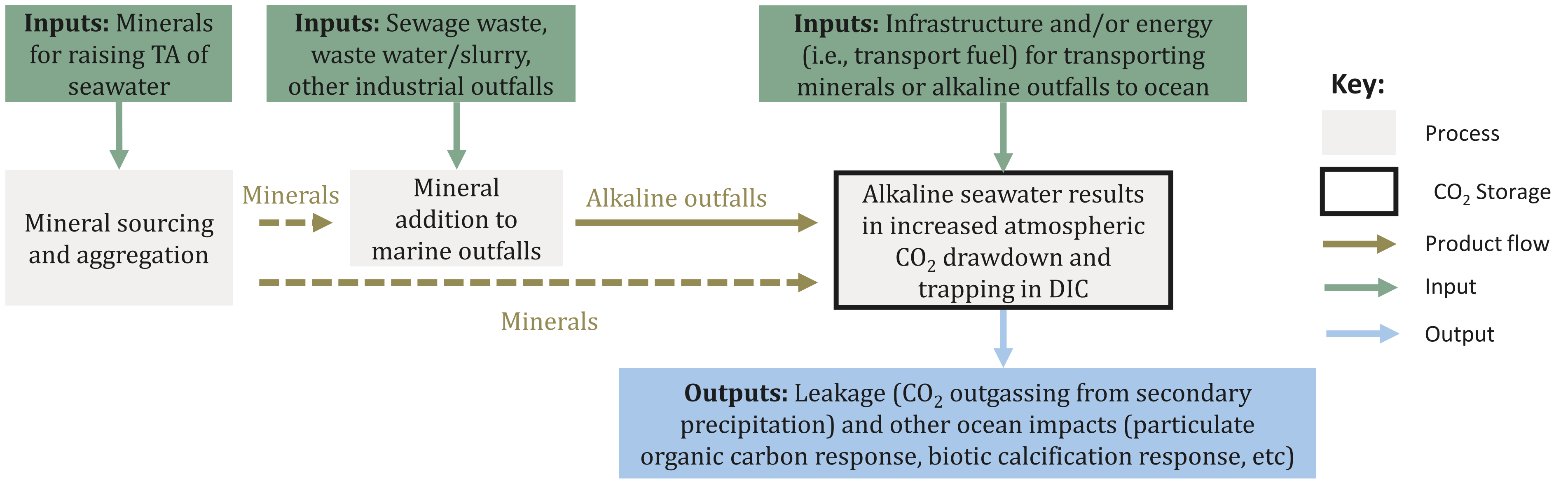
- **Ocean alkalinity enhancement (OAE)** increases the total relative alkalinity of seawater by capturing seawater and removing acid (i.e., HCl) via electrochemical techniques, or adding alkaline substances to marine outfalls and/or directly to the marine water column.
- **Electrochemical OAE techniques** increase alkalinity through acid removal. Surface layer seawater is removed and exposed to electrochemical techniques for separating acids and bases (see DOR slides). However, unlike in DOR where CO_2 is removed, electrochemical OAE projects remove acids (i.e., HCl) instead, creating a more alkaline solution due to the removal of H^+ ions. The removed acid may have a variety of fates, (e.g. be used in industry) so long as the acid is not returned to the ocean. When the acid-depleted seawater is returned to the ocean, greater CO_2 drawdown from the atmosphere occurs to re-equilibrate marine system pH.



Technology Overview and System Diagram – Ocean alkalinity enhancements (2/2)

OAE

- **Mineral OAE techniques** increase alkalinity through base addition (silicate, carbonate, or other mineral derivatives)* directly into the sea (coastal or open ocean) or in marine outfalls (i.e., treated sewage runoff) which are discharged into the ocean. When the alkalinity-increased seawater is added to the ocean, greater CO_2 drawdown from the atmosphere occurs to re-equilibrate marine system pH. The timing of mineral addition is expected to be important, as long-term mineral fate may be affected by biological and physical processes.
  - Some of the proposed minerals are abundant in Earth's crust, but the costs, logistics, and environmental/social footprints of mining and other industrial transformation activities (i.e., the calcination of limestone into quicklime) are to be considered, as are the impacts of metallic ions on marine biota.
  - Compatibility with the London Protocol (a voluntary international framework to reduce ocean dumping) is a current area of concern for mineral OAE techniques. OAE may be considered a form of "marine pollution" outlawed under the Protocol as originally written**. In 2022, the Protocol governing bodies identified four marine techniques (including OAE) as priority areas for legal and technical analysis in order to evaluate options for appropriate action and/or regulation within the scope of Protocol. However, OAE may currently be forbidden or restricted amongst Protocol Parties.
- Similar to DOR, there **are limited LCAs for OAE**. However, one LCA performed by Foteinis et al (2022) for mineral OAE suggested atmospheric removal potential of **-1034 kg CO_2 / tCaO.**



* Note that mineral OAE techniques are not to be confused with ocean fertilization techniques, which seek to add limiting nutrients (i.e., Fe) directly to the surface layer in order to facilitate increased phytoplankton growth. The efficacy of the iron fertilization has been subject to debate.

** While a 2013 Protocol Parties adopted an amendment governing "marine geoengineering" this is currently widely understood to likely only apply to ocean fertilization, and has not received full ratification

NASEM, 2021 – Link Foteinis et al., , 2022 – Link IMO 2022 statement – Link

Supply chain and LCA considerations (1/2)

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Acid capture from seawater	Energy inputs	The emissions association with the energy inputs to the electrochemical or other capture process, both electricity and heat where relevant.	• Carbon intensity of waste heat utilisation, and division between primary and secondary functions • Indirect impacts of energy generation, e.g. land use change, etc	**Uncertainty:** **Medium**
	Material inputs	Emissions associated with the consumed materials used in the electrochemical or other capture process (minerals, resin, membranes, etc).	• Potentially incomplete datasets for LCA on novel chemicals, such as degradation and lifetime • Quantification of emissions associated with waste product handling and potential recycling of key chemical components	**Uncertainty:** **Low**
	Total acid removal	Quantification of the mass of H+ removed from the captured seawater and subsequent Total Alkalinity raise.	• Mass of H+ evolved from the solution or formed in various acid forms	**Uncertainty:** **Low**
Atmospheric CO_2 drawdown via air-sea gas exchange	-	See LCA considerations for DOR	• See LCA considerations for DOR	**Uncertainty:** **High** **Impact:** **High**
Secondary impacts from alkaline seawater return to ocean	-	See LCA considerations for DOR	• See LCA considerations for DOR	**Uncertainty:** **High** **Impact:** **Medium**
Long-term fate of extracted acid (electro-chemical OAE)	Downstream use of acid	The removal of acid only results in a net CO_2 drawdown if the acid end-use does not result in the return of the H+ to the ocean (as a return of the acid would negate the increased net alkalinity of the returned seawater and reduce atmospheric drawdown).	• Any downstream use of removed acid, including its ultimate disposal method and tracked fate	**Uncertainty:** **Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Supply chain and LCA considerations (2/2)

OAE

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations • Frequency of replacement of infrastructure components that may degrade due to corrosion	**Uncertainty: Low**
Mineral sourcing and aggregation (mineral OAE)	Minerals	Mining and aggregation of the minerals from the subsurface or acquisition of minerals from commercial suppliers.	• Associated emissions with mineral mining and/or aggregation activities	**Uncertainty: Low**
Mineral addition to outfall or seawater (mineral OAE)	Outfall type and source	Source, material and disposal method of the outfalls which the minerals are added to, and rise in Total Alkalinity of outfall.	• Associated emissions with sourcing or potential creation of outfall stream, as well as outfall disposal method (if any energy is required for pipeline pumping, etc) • Quantification of the rise in Total Alkalinity (and thus subsequent atmospheric CO_2 drawdown potential) directly due to the addition of minerals to the outfall, including any secondary reactions which may reduce the concentration of dissolved anions, and alkalinity impacts of the outfall on the seawater.	**Uncertainty: Medium**
	Direct addition to seawater	Raise in system Total Alkalinity attributed to mineral addition	• Quantification of the raise in Total Alkalinity (and thus subsequent atmospheric CO_2 drawdown potential) directly due to the addition of minerals to the seawater, similar to electrochemical OAE. • Total Alkalinity released in the surface ocean is a function of particle size, dissolution rates, and sinking rates. Larger particle sizes may reduce dissolution rates or result in material sinking to depth or buried in sediment, complicating Total Alkalinity assessment (and subsequent atmospheric CO_2 drawdown potential). • Impacts of this uncertainty could be as high as 5-20% of removal potential*.	**Uncertainty: High** **Impact: Medium**
Mineral dispersal	Mineral dispersal and dissolution	Degree of mineral dissolution and tracking of dispersal in the surface mixed layer.	• Percentage of mineral dissolution (to determine release of anions which increase alkalinity). • Location of dispersal (mixed ocean layer or if minerals/dissolved ions have sunken to lower ocean layer(s)	**Uncertainty: Medium**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Identified options for direct/indirect measurement of inputs and outputs (1/2)

OAE

Process	Component	Parameter	Measurement Methods	
Acid removal from captured seawater (electrochemical OAE)	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
	Material inputs	Volume of materials consumed	Volumes consumed and associated emissions	I
		Carbon intensity of consumable materials	Cradle to grave LCA assessment of chemical inputs	I
	Infrastructure	Associated emissions	Cradle to grave LCA assessment of construction materials	I
	Total acid removal	Total mass of H^+ removed from system	H^+ removal measured directly as a metered output from the electrochemical system. Checked for consistency against operational data and characterization of the seawater effluent that has raised Total Alkalinity	I D
Mineral sourcing and aggregation (mineral OAE)	Minerals	Volumes of minerals consumed and emissions associated with mining and aggregation	Volumes consumed and associated emissions	I D
Mineral addition to outfall or seawater (mineral OAE)	Outfall type and source	Emissions with outfall source	Volume of outfall required per expected unit CO_2 drawdown and associated emissions	I D
	Direct addition to seawater	Total Alkalinity enhancement	Measurement of Total Alkalinity raised as a result of mineral addition	D I M

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Identified options for direct/indirect measurement of inputs and outputs (2/2)

OAE

Process	Component	Parameter	Measurement Methods
Long-term fate of extracted acid	Ensuring H+ removed from seawater is not returned to seawater	Operational records of project-level and commercial arrangements of long-term acid use	At the project level, it is possible to ascertain the likely end fate of produced acid using operational records. As this solution scales, acid disposal may become more of a challenge. I D
Atmospheric CO_2 drawdown via air-sea gas exchange	Atmospheric CO_2 (in various DIC forms)	Various DIC forms and associated changes in carbonate chemistry	In-situ measurements can potentially track post-deployment changes in pCO_2, pH, and DIC and deploy water mass tracers to help validate models of plume dispersal and atmospheric CO_2 drawdown The conversion of alkalinity to CO_2 removal is estimated to be 70-95% on a mol to mol basis M I D
Secondary impacts from alkaline seawater return to ocean	Secondary precipitation	Formation of secondary precipitates such as $CaCO_3$	Seawater sampling, laboratory experiments and geochemical mass balance modelling M I D
	Biotic calcification	Quantification of biotic calcification	Seawater sampling, laboratory experiments and geochemical mass balance modelling M I D
Tracing rate of mineral dissolution and dispersal	Mineral dissolution and dispersal rate	Mineral dissolution and dispersal rate	Overall CO_2 uptake efficiency can be estimated using seawater chemistry modelling software and known equations, which can be validated by measurements of bicarbonate concentrations or total alkalinity in the water column. M I D

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Key uncertainties

OAE

Process	Uncertainty Type	Description	GGR Standard Questions
Long-term fate of acid removal (electro-chemical OAE)	Operational use of acid once it is removed and sold for commercial or industrial use	• Any source of acid from the process that ultimately reaches the ocean or interacts with terrestrial carbonates prior to being neutralised will counteract claimed alkalinity enhancement. At the project level, it is possible to ascertain the likely end fate of produced acid using operational records. As this solution scales, acid disposal may become more challenging.	• Does the standard measure the potential for H+ return to the ocean based on final end-use of the extracted acid (i.e., waste disposal, runoff, etc)? • Can this be mitigated by a closed loop system? • What level of detail is required in tracking acid end-use?
Air-sea gas exchange	Measurement: Atmospheric CO_2 (in various DIC forms) and changes in carbonate chemistry	• Quantifying the mass of CO_2 which has been drawn down from the atmosphere as a result of alkalinity enhancements of returned seawater, relative to the degassed CO_2 returned to atmosphere • The precise dispersal of DIC-depleted seawater in the water column (location, residence time at surface, etc) • Residence time of absorbed atmospheric CO_2 within seawater DIC (i.e., how long is CO_2 "trapped" as bicarbonate before re-aligning with geological carbon cycles such as shell formation, seafloor subduction and recycling, etc)	• What is the modelling method of quantifying the mass of CO_2 which has been absorbed from atmosphere directly as a result of OAE activities? Have these models shown to be both precise and accurate with in situ measurements? • What is the method for tracking the dispersal of DIC-depleted seawater once it is returned to ocean? • Should absorbed atmospheric CO_2 be considered "trapped" if incorporated into DIC? • Is the potential for degassing or other potential routes to return to atmospheric CO_2 measured?

Key uncertainties

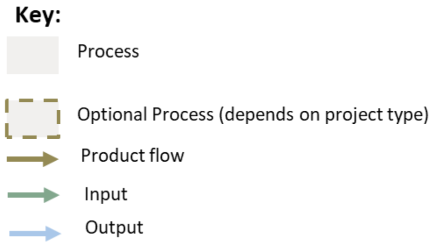
OAE

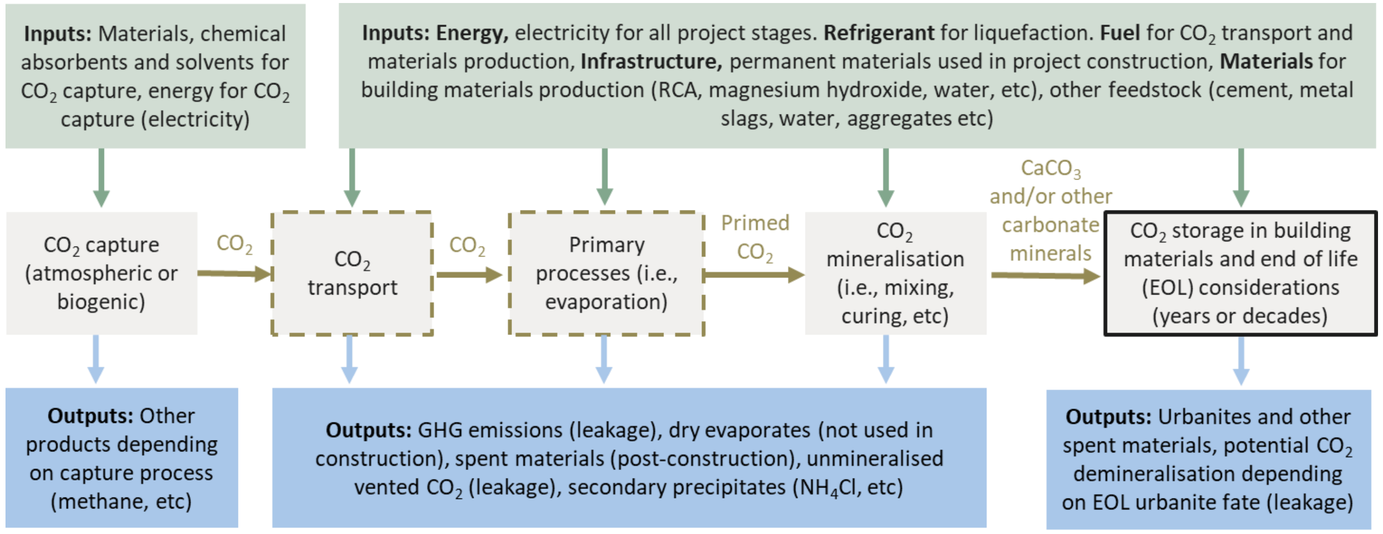
Process	Uncertainty Type	Description	GGR Standard Questions
Secondary precipitation	Measurement: Formation of secondary precipitates such as $CaCO_3$	The removal of acid from the seawater will cause pH shifts, which may result in abiotic precipitation of other minerals (i.e., brucite, etc). In order to equilibrate with this secondary precipitation, there could be an increase in oceanic dissolved CO_2 turning back into a gas and being released back to the atmosphere (outgassing). While the extent of this process and its magnitude in response to OAE is currently unclear, any CO_2 released back into the atmosphere from the oceans as a result of OAE projects must be subtracted from the negative emissions potential of the project.	• Should the standard measure the level of secondary precipitation as a proxy for CO_2 outgassing, and should this be subtracted from the net GGR potential? • What methods should be acceptable for tracking and quantifying secondary precipitation and/or CO_2 outgassing?
Biotic calcification response	Measurement: Quantification of biotic calcification	Since calcification releases CO_2, any changes to the rate of biotic calcification in response to shifts in pH and dissolved inorganic carbon (DIC) concentrations driven by the OAE process must be considered. Changes in biotic calcification rates could occur in both coastal and open ocean waters, and at the level of individual calcifiers or calcifier populations. In practice, quantifying the biotic calcification response to carbon-depleted water may pose significant spatial, temporal, and signal-to-noise challenges.	• Can the rates of biotic calcification as a response to OAE activities be accurately and precisely tracked in order to be subtracted from the GGR performance?
Mineral dispersal	Measurement: Tracking mineral dissolution in the surface water mixed layer	Alkaline minerals need to dissolve in the surface mixed layer in order to increase alkalinity and facilitate atmospheric CO_2 drawdown. This is due to chemical reactions occurring primarily between ions, released during dissolution, rather than chemically stable minerals. Mineral OAE projects must track the rate of dissolution of added minerals, as well as the relative location in the water column (dissolution below the surface mixed layer will likely have very limited drawdown potential over a short-term timescale due to a lack of exposure to atmospheric CO_2).	• Does the standard have a means of effectively quantifying and tracking mineral dispersal, including where in the water column the minerals move to? • Does the standard have a means of effectively quantifying and tracking dissolution rate and location of dissolution?

Carbon negative building materials

- **Carbon negative building materials** result in GGRs by sequestering **atmospheric** (either through DAC or natural atmospheric absorption via curing/carbonation) **or biogenic CO_2*** into a variety of **concretes or other building materials** (tiles, supplementary cement materials, etc)**.**
- CO_2 can be used as a secure building material as the molecule may be incorporated into **carbonates (X-CO_3)** which, outside of severe pressure/temperature/acidic conditions, represents a kinetically stable form of **mineralised CO_2.**
- CO_2 may be incorporated into concretes using a variety of different processes.
  - These processes may either capture atmospheric or biogenic CO_2 onsite, or form strategic partnerships with DACCS or BECCS companies to supply captured CO_2.
  - Production methods may have a variety of necessary primary processes to prepare the CO_2 for mineralisation (i.e., evaporation).
  - During concrete mixing, CO_2 can be incorporated with water, aggregates and cement to mineralise into carbonates within the concrete mixture (i.e., CarbonCure). Concrete can also incorporate supplementary cementitious materials (slags, fly ash, etc.) and other low carbon feedstocks.
  - Curing of precast concrete can be undertaken in a elevated CO_2 atmosphere to increase CO_2 mineralisation (i.e., Carbicrete).
  - Complete mineralisation of all the available CO_2 may not be achieved (depending on the available mineral analytes) with any remaining CO_2 vented into the atmosphere.
  - Depending on feedstocks, secondary precipitates may also be created from the process through further crystallisation and/or p article separation (i.e., NH_4Cl). These may be used or sold for other building/chemical purposes.
- The carbon negative cements/concretes are generally expected to **outlive the structures they build**. Fate of the **urbanites** (concrete rubble pieces) or other carbon-negative post-demolition materials should be considered. Should these aggregates be recycled, further processes (i.e., chemical recycling p rocesses) must **not release mineralised CO_2.**

*There are a number of technologies which capture and mineralise point source CO_2 from industrial sources or from limestone (i.e., Portland cement). However, this CO_2 is usually not atmospheric nor biogenic in origin, meaning that while the process results in decarbonisation, it is not GGR.





Tiefenthaler et al, 2021 – Link
Batuecas et al, 2021 – Link
Ravikumar et al, 2021 – Link
Mahoutian and Shao, 2016 – Link

Summary of existing LCA emissions calculations

Buildings

- **Carbon negative building materials** represents a diverse array of processes, products, and sources of CO_2, therefore **comparing LCAs is challenging**, as there are significant deviations in project types and LCA system boundaries. LCAs methodologies are largely **academic or project-driven**, with a lack of standardisation in approaches.
- A current best practice is to present **CO_2 removal per unit product**. **Important LCA considerations** [6] for carbon negative materials are typically:
    - Source of CO_2 and assessment of biogenic or atmospheric carbon (also a major potential source of emissions)
    - Carbon sequestration yield, as the associated emissions with different production methods varies, and a significant volume of CO_2 which is not mineralised may be vented
    - Counterfactual emissions from incumbent building material production used to assess "reduction of emissions" against atmospheric removals
    - Longevity/permanence of end product (if considered), as end of life (EOL) processes (years to decades depending on building construction, use and demolition) may release the mineralised CO_2 depending on EOL treatment of the urbanites (post-demolition rubble).
- There has been no large-scale review and comparison for LCA results of carbon-negative building materials (likely due to complexity, diversity and nascent nature). However, a 2020 review [7] of LCA methodologies for timber construction (not considered in this section) found the **LCA error to be 35 – 200%.**

Reference	Project type	Negative emissions potential	Carbon removal efficiency (if listed)
[1] Tiefenthaler et al., 2021	Biogenic CO_2 producing recycled concrete aggregate (RCA)	- 1 $kgCO_2$ / 64 $kgCO_2$ emitted	93.6%
[2] Cavalett et al., 2022	Biogenic CO_2 producing cement clinker	- 24 to -169 gCO_2 / kg clinker	-
[3] CarbiCrete independent LCA (Carbon Consult Group)	Atmospheric CO_2 producing CMU (concrete masonry units)	- 1,000 gCO_2 / kg CMU	-
[4] Mahoutian and Shao, 2016	Atmospheric CO_2 producing steel-bond concrete blocks	- 0.09 gCO_2 / kg*	-
[5] Chen et al., 2022	Biogenic CO_2 producing biochar particleboard	- 137 gCO_2 / kg particleboard**	-

* 0.23 $kgCO_2$ removed for $1m^3$ block (2545 kg/m^3)

** 137 $kgCO_2$ removed for 1 tonne particleboard

[1] Link; [2] Link; [3] Link; [4] Link; [5] Link; [6] Some GGR standards indicate that the product carbon removal potential may also include comparisons to the alternative reference product (Puro.earth., 2022 – Link); [7] Link

Supply chain and LCA considerations (1/2)

Buildings

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
CO_2 capture (atmospheric or biogenic)	Energy inputs	• See LCA considerations under DACCS • See LCA considerations under BECCS	• See LCA considerations under DACCS • See LCA considerations under BECCS	**Uncertainty: Medium**
	Material inputs	• See LCA considerations under DACCS • See LCA considerations under BECCS	• See LCA considerations under DACCS • See LCA considerations under BECCS	**Uncertainty: Low**
	Biomass feedstock	• See LCA considerations under BECCS	• See LCA considerations under BECCS	**Uncertainty: Medium**
CO_2 Transport	Energy inputs	• See LCA considerations under DACCS	• See LCA considerations under DACCS	**Uncertainty: Low**
	Leakage	• See LCA considerations under DACCS	• See LCA considerations under DACCS	**Uncertainty: Medium**
Primary processes	Energy inputs	Source of electricity/heat required for primary preparation processes of captured CO_2	• Energy inputs will vary widely depending on the processes required	**Uncertainty: Low**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.

Supply chain and LCA considerations (2/2)

Buildings

Process	Component	Description of component	Key Considerations	Method Uncertainty & Impact*
CO_2 mineralisation (mixing / curing)	Energy inputs	Electricity and heat used to power mixing and curing processes during which mineralisation occurs	• Carbon intensity of waste heat utilisation • Indirect impacts of energy generation, e.g. land use change, mineral requirements • Energy inputs will vary substantially depending on the configuration of the project archetype	**Uncertainty:** **Low**
	Material inputs	All material inputs consumed in the production of concrete. This may include water, aggregates, cements, and any other supplementary cementitious materials (slags, fly ash, etc.).	• Quantification of emissions associated with materials sourcing • Potential recycling of key chemical components • System boundary and quantification of the carbon intensity of waste materials from other sectors, especially if they require upgrading	**Uncertainty:** **Medium**
	Leakage (Unmineralised CO_2)	Any CO_2 which did not react to form mineral precipitates, and which is vented and released into the atmosphere	• Mass of CO_2 released into the atmosphere must be subtracted from the total GGR potential of the process	**Uncertainty:** **Low**
CO_2 Storage in buildings	Leakage (Demineralisation and EOL)	Long-term fate of carbonate minerals in buildings (post-demolition), including any recycling processes (physical and chemical)	• System boundary consideration for the EOL recycling of concrete and how this effects overall carbon removal • Liability for ensuring the lifetime of materials is achieved • Ensure demand for building materials is additional • Research into the LCA impact of CO2 leakage (degradation) from carbon negative buildings is still be conducted, with early modelling results coming from the Argonne National Laboratory[1] (currently understood to be biofuels based with the likely intention of expanding scope to buildings).	**Uncertainty:** **High** **Impact:** **Medium**
Full chain	Infrastructure	See general LCA considerations	• See general LCA considerations	**Uncertainty:** **Low**

* Indicative uncertainty impact ratings are only provided for components with "high" uncertainty ratings.
[1] Argonne National Laboratory, 2021 – Link

Identified options for direct/indirect measurement of inputs and outputs (1/2)

Buildings

Process	Component	Parameter	Measurement Methods	
CO_2 capture (atmospheric or biogenic)	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
		Carbon Intensity of Energy Supply	Cradle to grave LCA of energy generation and connection, including grid reinforcement infrastructure	I
	Material inputs	Volume of materials consumed	Volumes consumed, determined for example through receipts for purchased materials	D
		Carbon intensity of consumable materials	Cradle to grave LCA assessment of chemical inputs	I
	Biomass feedstock	See LCA measurements under BECCS	See LCA measurements under BECCS	D
CO_2 Transport	Energy inputs	Electricity/Fuel consumption	Measurement of electricity consumed using an electricity meter / Fuel efficiency and distance travelled	I
		Carbon intensity of electricity/fuel	Cradle to grave LCA of electricity/fuel type	D
	Leakage	CO_2 leakage	Volumetric flowmeter before and after transport.	I
Primary processes	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
		Carbon Intensity of Energy Supply	Cradle to grave LCA of energy generation and connection, including grid reinforcement infrastructure	I

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Identified options for direct/indirect measurement of inputs and outputs (2/2)

Buildings

Process	Component	Parameter	Measurement Methods	
CO_2 mineralisation (mixing / curing)	Energy inputs	Energy consumption	Measurement of electricity consumed, or heat consumed based on flowrate and temperature	D
		Carbon Intensity of Energy Supply	Cradle to grave LCA of energy generation	I
	Material inputs	Volume of materials consumed	Volumes consumed, determined for example through receipts for purchased materials	D
		Carbon intensity of consumable materials	Cradle to grave LCA assessment of all material inputs	I
	Leakage (Unmineralized CO_2)	Mass of CO_2 contained in precipitates	Batch sample testing and volumetric flow readings at release stack	D I
CO_2 Storage in buildings	Leakage (Demineralisation and EOL)	End use of materials (buildings, etc), lifetime of buildings and EOL deconstruction or recycling fates	At the project level, it is possible to ascertain the likely end fate of carbon negative building products using operational records. As this solution scales, tracking the exact use, lifetime and EOL treatment of all produced and sold carbon negative materials will likely prove challenging.	D I
Full chain	Infrastructure	Volume of materials used	Volumes used in construction, determined for example through technical design drawings or receipts for purchased materials	D
		Carbon intensity of construction materials	Cradle to grave LCA assessment of construction materials	I

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Key uncertainties

Buildings

Process	Uncertainty Type	Description	GGR Standard Questions
CO_2 capture (atmospheric)	Methodology: Energy Input	• See key uncertainties under DACCS	• See key uncertainties under DACCS
CO_2 capture (biogenic)	Methodology: All feedstock components	• See key uncertainties under BECCS	• See key uncertainties under BECCS
CO_2 capture (biogenic)	Methodology: Material feedstock	• See key uncertainties under BECCS	• See key uncertainties under BECCS
CO_2 mineralisation (mixing / curing)	Measurement: Materials input	The carbon intensity of other feedstock aggregates mixed with CO_2 to create carbon-negative products. These may be virgin materials or waste products which will affect the carbon intensity of the final product.	• What is the production process and what are the volumes and carbon intensities of the other required feedstocks?
CO_2 mineralisation (mixing / curing)	Measurement: Mass of CO_2 captured	Secondary processes (i.e., curing) may naturally sequester additional CO_2. If this CO_2 is atmospheric then this gives an additional opportunity for GGR. However, quantifying the mass of CO_2 sequestered may be challenging without specialised measurement equipment.	• What is the mass and source of CO_2 sequestered in secondary processes, and can this be accurately recorded? • What is the variability between sequestration rates?
CO_2 storage in buildings	Methodology: Long-term fate of mineralised CO_2	The construction projects that incorporate carbon-negative building materials may be challenging to track as the solution scales. Projects may have a diverse lifespan of years to decades. Should buildings be demolished, the EOL fate of the carbon negative materials would need to be tracked [1], as potential physical or chemical recycling or disposal processes may re-release the sequestered CO_2. Liability for ensuring GGR may be a point of contention.	• In which projects will the carbon negative building materials be used in? • What is the standing lifecycle of the constructed buildings? • What is the post-demolition disposal and/or recycling process for the urbanites or other rubble? • Is there a liability transfer between the carbon negative building material producer and construction company?

[1] Argonne National Laboratory, 2021 – Link

Approach to task 3: review of existing GGR standards and methodologies

Approach

- In this task we reviewed existing and proposed standards and methodologies applicable to GHG accounting of GGR technologies. Priority was given to GGR standards that included MRV requirements (see table below).
- Our analysis was based on the information and documentation available as of mid-June 2023. Updates introduced after this period, such as the draft DACCS and BECCS methodologies developed by CCS+ Initiative under Verra, were not considered.
- The following slides include details about how the main GHG accounting and MRV provisions of each of the identified standards were documented.

Standard	DACCS	BECCS	Biochar	EW	Oceans	Concrete
Puro Earth	Dark Green	Dark Green	Dark Green	Dark Green	Tan	Dark Green
Verra	Tan	Tan	Dark Green	Tan	Tan	Dark Green
Gold Standard	Tan	Dark Green	Tan	Tan	Tan	Dark Green
American Carbon Registry	Light Green	Light Green	Tan	Tan	Tan	Tan
Climate Action Reserve	Tan	Tan	Light Green	Tan	Tan	Tan
Climeworks, Carbfix	Dark Green					
Carbon Standards Int.	Tan	Tan	Dark Green	Dark Green	Tan	Tan
Planetary					Dark Green	

Colour code for table: Dark Green – existing methodologies; Light Green – publicly available draft methodologies under development; Tan – potential future methodology, but no public drafts or expansion plans; Blank – the standard is not expected to expand to other GGR technologies

Below is a list of additional standards or frameworks with relevance for GGR technologies. These are excluded from the detailed analysis but have been covered at a higher level and informed other aspects of the study – such as determination of the assessment criteria.

Category	Examples	Description
Wider GHG standards and GGR best practices	Oxford Offsetting Principles, IC-VCM, GHG Protocol, IPCC Guidelines, ISO LCA standards, CORSIA, EU Carbon Removal Certification Framework	These resources include valuable principles for standards or methodologies to follow. They can be used to shape GGR standards or to assess their merits but are not certification schemes themselves. Brief descriptions of some of these key resources are provided in this section.
CCS standards	ISO CCS standards, CCS+ initiative, EU CCS Directive, California LCFS, 45Q	Most CCS projects must follow national CCS regulations and their associated standards. Therefore, in addition to the GGR standards in scope, we decided to include a brief assessment of the UK 2010 CO_2 (Licensing, etc.) Storage Regulations, which will directly be applicable to any UK DACCS and BECCS project.
Other schemes	Frontier, Be Zero, Microsoft, Shopify, XPRIZE	These schemes may be viewed as buyer's guidelines or general principles to select promising GGR projects for investments but are not independent certification standards. Therefore, they have been excluded from detailed assessment, but this section provides a brief overview of some of the more relevant standards under this category.

Template used to collect standard-level information (1/2)

General description	
Description and classification	• Full name of the standard / registry as well as name of the credit issued, if it has one. • **Classification**: General standard for carbon reduction and removals; general standard for carbon removals only; stand-alone methodology for one GGR technology; collection of best practices for standards; buyer's guidelines for GGR purchasing; other – please specify • **Background**: When and how was the standard created? What is its purpose? Compliance or voluntary markets? Any restriction on how the credits can be used? What is the legal geographical coverage?
GGR coverage	• List of GGR technologies covered, indicating if methodologies are currently active, being developed or expected to be developed in the future. • Any limits to specific sub-types of technologies? For example, BECCS power included but BECCS energy from waste excluded. • List of GGRs covered that are outside the scope of this project for background. Ex: Verra / Gold standard certify nature-based removals.
Governance structure	• Who owns the organization? • What are important governance bodies? How are decisions taken (e.g., consensus, vote, etc)? • **Methodology development** – brief description of process for developing new methodologies. Is the process transparent? Is there an independent scientific advisory board? Is there a public consultation process? Is there a way to submit variation orders to existing methodologies for minor changes? Are there provisions for periodic methodology reviews?
Information rights	Can any third-party use/endorse/adapt the standard without paying any royalty? Who holds the IP?
Number of projects / credits	Brief overview of the number of projects registered and credits issued to date, registrations in last year, specific numbers for carbon removals and individual GGR technologies, if available. Details depend on availability and cost data will be excluded.
Sustainability requirements	• Are there additional sustainability requirements (environmental or social-economic)? • Are these requirements technology specific or general guidelines?
Key documents	List and links to key documents including methodologies, sustainability requirements, traceability requirements and assurance system.

Template used to collect standard-level information (2/2)

MRV specifics	
MRV and accounting basics	**Baselines** • How is the baseline determined (e.g., by modelling or field testing)? • Is the baseline assumed to be zero emissions? Are there any important components missing from the baseline? • Does / how frequently baseline updates? **Additionality** • Is additionality assumed for specific activities or does it need to be proven? Is demonstration required at intervals (every 7 years etc.)? • Which tests are required or allowed: financial test, common practice test, barriers test (technological, cultural, other), not required by local regulations? **Permanence** • Is there a buffer pool? Or is a discount factor applied to account for non-permanence? • Is there onsite verification? • For how long is the project required to maintain and monitor the storage site? • Are there provisions / requirements around transfer of liability to the government?
Verification and crediting	• **Crediting –** Which project proponent receives the credit? Are there one or two credits (usually covering CO2 capture and storage activities separately)? Is there a public registry? For how long can projects claim credits? • How is verification conducted (e.g., self-reporting, third party audit, etc.)? • Who are the independent verifiers? Do the delivery, trade and acquisition of carbon credits belong to the scope of verification ? • Are physical onsite measurements or inspections required? If so, how frequently is this required?
Treatment of uncertainty	• Are there any provisions on treating uncertainty in calculations? • If yes, are they conservative approaches, such as assuming a discount factor rather than ignoring certain types of emissions? • Are the treatment of uncertainties project / technology specific or uniform across the whole standard?

Approach to task 4: assessment of treatment of individual GGR technologies under each standard / methodology

- In this task we **combined learnings from Tasks 2 and 3 to assess whether the key LCA methodological and MRV questions (assessed in Task 2) are adequately addressed by each GGR standard or methodology.**
  - For each **GGR scheme with an MRV mechanism** (green and brown boxes on the table showing standards in scope), we analysed in depth how the key LCA / MRV considerations identified in Task 2 are addressed for each technology. This directly built on the template for key uncertainties provided in Task 2.
  - For **GGR technologies that are not currently covered by a standard** (e.g., ocean-based removals under Verra), we commented on the ease of developing new methodologies under these standards considering synergies with existing provisions for other technologies.
- Lastly, provisions of the methodologies addressing key LCA / MRV concerns were assigned a SATISFACTORY, NEUTRAL or NEEDS IMPROVEMENT rating depending on our satisfaction with how well they aligned with best practices.

Illustration of approach to methodology assessments in task 4

Process	Uncertainty Type	Approach of the methodology
CO_2 capture	Methodology: Energy Input	• Xxx [SATISFACTORY] • Xxx [NEEDS IMPROVEMENT]

The colour code used to assess GGR schemes is as follows:

- [SATISFACTORY] – The methodology has specific requirements and/or guidance to fully address the LCA/MRV issue.
- [NEUTRAL] – The methodology addresses the LCA/MRV issue partially and/or no significant concern or risk was identified regarding the accuracy of GHG accounting or reporting.
- [NEEDS IMPROVEMENT] – The methodology does not or insufficiently address the issue, which puts the accuracy of the GHG accounting/reporting at risk.

NB: Minor and major concerns are further distinguished in Task 5.

Stakeholder engagement phase 2: Draft outputs of this section were shared with the scheme owners (without colour code assessments). Feedback received was used to further improve standard descriptions*. The following standards provided feedback: Puro Earth, Gold Standard, American Carbon Registry, Climate Action Reserve, and Planetary. Others were unable to provide feedback within the consultation period.

* Note that this does not imply endorsement of the outputs by any of the standards. Treatment of feedback received was under the sole discretion of the authors.

Overview: Puro Earth (1/2)

DACCS | BECCS | Biochar | ERW | Buildings

General description	
Description and classification	• **Puro Earth (Puro)** is a carbon crediting platform specialising for GGRs. It issues **CO2 Removal Certificates (CORCs)** and maintains the **Puro Registry** online. • **Classification**: Puro is a general standard for carbon removals only. • **Background**: Puro is privately owned and started operations in 2019. It is based in Finland and was initially conceived by Fortum, a leading Nordic energy company. In 2021, Nasdaq acquired the majority stake in Puro. Currently Puro operates globally in the voluntary carbon removal markets.
GGR coverage	Puro has active methodologies for the following GGR technologies: geological storage (joint methodology for DACCS and all types of BECCS), biochar, enhanced rock weathering, carbonated materials (including building materials), and woody biomass burial (not in scope of this study). Puro only certifies GGRs that can offer high durability (specifically at least 100 years of permanence, which excludes most nature-based options).
Governance structure	• Puro is majority owned by Nasdaq, which is owned by the US-based for-profit Nasdaq Inc. Puro Earth is governed by the **Board of Directors**, however, the board authorised an independent **Advisory Board** to manage the Puro Standard and crediting rules, including recommending any future changes. The Advisory Board is made up of members with different backgrounds relevant to carbon removals crediting and they are not direct employees of Puro. • **Methodology development** – The Advisory Board has the mandate to update the existing methodologies if they believe sufficient changes have happened in the science or best acceptable practices. Any such recommended updates are published for public comments online and responses are also shared by Puro Earth. Development of new methodologies usually take around 6 months and involve collaboration of a working group of key individuals and experts and at least two project proponents. Draft methodologies are shared publicly for feedback and comments are internally discussed and addressed. The Advisory Board independently reviews the draft and provides the final approval. There are no fees associated with methodology development.
Information rights	Puro Earth and all of their IP is privately owned. Any official future partnership would require bilateral agreements and a likely financial contribution.
Number of projects / credits	In 2022, 225,000 CORCs were issued by Puro, which represented a 250% growth from 2021. According to the Puro Registry, by early April 2023, CORCs were retired from a total of 44 production facilities spanning 18 countries. All retired CORCs to date were created via biochar, wooden building elements and soil amendments (where the latter two methodologies are now discontinued).
Sustainability requirements	All methodologies include a generic environmental and social safeguards clause requiring projects to demonstrate that they do no significant harm, which can be done through an Environmental Impact Assessment, obtaining all relevant permits, providing other documents approved by the Issuing Body and developing projects with informed consent of local stakeholders / communities. The enhanced rock weathering methodology includes additional detailed specific provisions such as requiring an environmental risk assessment backed by lab testing for toxic elements, authorisation to spread materials on land, sustainable and safe sourcing of raw materials, a monitoring plan, evidence of engagement with the local community, impact assessment on the local community and demonstration of occupational health and safety measures. Also, the biochar methodology requires testing for toxic elements such as heavy metals and polycyclic aromatic hydrocarbons. Methodologies require biomass feedstocks to be sustainable, as defined by the EU Directive RED II for BECCS and European Biochar Certificate or IPCC Appendix 4 - Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments for biochar.
Key documents	• General Puro Standard Rules – Link • Puro Approved Methodologies – Link • Additionality Requirements – Link • Validation & Verification Requirements – Link • Methodology Development Outline – Link

Overview: Puro Earth (2/2)

DACCS | BECCS | Biochar | ERW | Buildings

MRV specifics	
MRV and accounting basics	**Baselines –** Puro standard requires projects to select a baseline and refers to CDM's "Combined tool to identify the baseline scenario and demonstrate additionality" for reference. The baseline scenario should realistically reflect what would happen in the absence of additional carbon finance. Puro only credits for net removals against a baseline set at zero at the highest. However, if baseline also has negative emissions, this is taken into consideration, such as natural CO_2 removal through carbonation of reactive rocks without the project activities. **Additionality** • Additionality is not assumed for any activity; it must be proven on a case-by-case basis. Additionality check is part of Facility Audit, which are performed every 5 years. • Projects are required to demonstrate that their activities are **not developed as a result of existing laws, regulations or other binding obligations.** • Puro requires all projects to conduct a financial additionality analysis, which may follow CDM's Investment Analysis Tool. Projects must submit full financial analysis for their activities and other plausible counterfactuals to prove that the project activity becomes more attractive than the alternatives when CORC revenues are included. The financial analysis should include a sensitivity analysis to determine the likelihood of the selected scenario. • Double counting is avoided by the use of Puro Registry and requiring all final users of activity by-products (final consumers of biochar, building materials, farmers, etc.) to agree not to make any carbon removal claims from using these products if the credits are unbundled from the physical products. **Permanence –** Puro requires a minimum CO_2 removal durability of 100 years. Permanent biochar is quantified at 100 years mark accounting for expected re-emissions through decay during the first 100 years. Other methodologies are labelled to yield 1000-year permanence. It is assumed that risk of reversal after CO_2 mineralisation (enhanced weathering and building materials) or geologic storage (DACCS and BECCS) is minimal, therefore no buffer pool is created for potential future leakages. CORC generation via enhanced weathering requires annual field tests to prove removal volumes, so monitoring throughout the project time horizon can be assumed. Other methodologies do not explicitly require ongoing monitoring of CO_2 sinks (e.g., farms with biochar, buildings or geologic storage sites) and have no specific provisions for transfer of liability to the government. **However, BECCS and DACCS activities are required to comply with the EU CCS Directive or US EPA regulations for CO_2 storage** (or other similar national regulations), which do have their own monitoring and liability transfer provisions.
Verification and crediting	**Crediting** – CORCs can be issued for activities that took place a maximum of 18 months before the date of issuance. Each CORC represents one tonne of net CO_2 removed. Unretired CORCs are automatically removed from the registry after five years. CORCs are issued to CO_2 Removal Suppliers, which are entities legally responsible for end to end carbon removal activities. The point of credit creation depends on specific methodologies but it is usually when CO_2 storage is inspected or durable end product (biochar or carbonated material) is created for acceptable end uses. In 2022, Puro introduced a new type of credit called **pre-CORC**, which represents one net tonne of future CO_2 removal. This is an instrument customers can use to pre-pay for credits prior or at the start of projects and pre-CORCs are turned into regular CORCs when activities are verified. Independent third party verifiers, called Production Facility Auditors, must assess the eligibility of new projects during registration to ensure compliance with the standard and methodology requirements, issuing an audit report. CO_2 Removal Suppliers then issue regular output reports (monthly to annual) and receive CORCs after an initial review by the Issuing Body. Annual Output Audits are carried by independent third party auditors to verify the evidence and issuance of correct number of credits. Initial facility audits happen on site, however, Output Audits are allowed to happen remotely. All lead auditors must be accredited by recognised national or international programmes (such as ISO 14065, ISO 14066, CDM Accreditation Standard for Designated Operational Entities, or other similar standards) and be approved by Puro.
Treatment of uncertainty	There are no systematic requirements for treatment of uncertainties. The methodology for geologic storage requires using conservative end of a range of values if uncertainty exists. Methodologies for carbonated building elements and biochar do not include provisions for treating uncertainties. The methodology for enhanced rock weathering explicitly requires quantification and estimation of uncertainties due to spatial and temporal heterogeneity arising from simulations and physical site sampling. This methodology also requires project developers to present a plan to mitigate uncertainties. The methodology recommends the following specific measures: sanity checks, internal robustness checks, mathematical evaluation of uncertainty and the possibility to optimise the model, for example through identifying most important contributors to GGR.

Puro Earth's approach to certifying DACCS

DACCS

Additional information: According to Puro's methodology for Geologically Stored Carbon, chemical or membrane separation methods are allowed for DACCS. Captured CO_2 may be stored in dedicated geologic formations or be used in enhanced oil recovery (EOR), although an upcoming update is expected to exclude EOR activities.

Process	Uncertainty Type	Approach of the methodology
CO2 capture	Methodology: Energy Input	• Wider system impacts of energy used for carbon capture is explicitly excluded from quantification of net removals as the methodology suggests that "CO_2 Removal Suppliers are not responsible for the availability of renewable electricity in the local market." Self generated and contractually procured energy (e.g., through power purchase agreements) are treated equally by the methodology. Land use change implications of additional renewable energy are also not considered. [NEEDS IMPROVEMENT] Embedded emissions in materials for additional renewable energy sources are accounted for. [SATISFACTORY] • The methodology has no specific provisions relating to waste heat utilisation, however, the methodology excludes emissions from activities not carried for the sole purpose of carbon removal, so waste heat would be assumed zero emissions. [SATISFACTORY] • The general "do no net harm" provision requires projects to not cause deforestation, loss of arable land and biodiversity, which can apply to the environmental impacts of deploying new power generation capacity. [SATISFACTORY]
CO2 transport and storage	Methodology: Energy Input	The methodology does not include any specific provisions relating to use of multiple different transport or storage modes, however, CO_2 logistics and storage operators are required to report volumes of CO_2 received and passed on the next stage (storage or injection), which would be required of each transport and storage operator is more than one. If the transport and storage systems serve multiple customers, operators are required to report carbon efficiencies of their systems (CO_2 passed on / CO_2 received) to enable calculation of CO_2 leakage. [SATISFACTORY]
Geological storage	Measurement: CO_2 migration, trapping and leakage	• The methodology does not have any specific provisions or requirements about storage site monitoring, leakage detection, leakage quantification, modelling of storage site behaviour, physical sampling of any kind or liability transfer to the government after project activities. The only required pieces of evidence are shipping documentations indicating that the CO_2 is delivered to storage site operators intended for permanent storage and proof that the **storage site is classified and permitted under EU CCS Regulation, US EPA Regulation or other CCS regulations following similar requirements.** It is implicitly assumed that compliance with such regulations is sufficient to satisfy storage related MRV concerns. [NEEDS IMPROVEMENT] • Puro Earth used to maintain a pre-issuance buffer pool of 10% of a project's credits (to be used in case of leakage), but this is expected to be removed in an upcoming update. It may be implicitly assumed that the local CCS regulations cover remediation in case of leakage. [NEEDS IMPROVEMENT] • The methodology does not cover storage through rapid CO_2 mineralisation (e.g., approach used by companies such as Carbfix and 44.01) because it references CO_2 storage types permitted through the EU CCS Directive and USA EPA Underground Injection Control regulations, which do not cover rapid mineralisation. However, Puro's newly updated carbonated materials methodology expanded its scope beyond building materials to include in situ mineralisation, so these types of DACCS plants may still be certified under Puro. [SATISFACTORY]

Puro Earth's approach to certifying BECCS

BECCS

Additional information: According to Puro's methodology for Geologically Stored Carbon, the following types of BECCS are explicitly listed as eligible: combustion of biomass/biogas/bioliquids, waste from energy, biogas upgrading, biogenic carbon from industrial processes, and biogenic carbon containing substances (storage in non-CO2 form). Captured carbon may be stored in dedicated geologic formations or be used in enhanced oil recovery (EOR), although an upcoming update is expected to exclude EOR activities.

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: All feedstock components	• The methodology does not explicitly discuss the types of default parameters that can be used in LCA calculations and iLUC emissions. However, it requires a cradle-to-gate emissions accounting for sourcing biomass (only if purpose grown for BECCS) according to requirements of the EU RED II Directive or similar criteria if the project is outside the jurisdiction of RED II. Therefore, biomass accounting is expected to be **relatively robust in regions with well-defined sustainability regulations**. [NEUTRAL] • Carbon payback time is not mentioned or considered in the methodology.
Feedstock production	Methodology: Material inputs	• The methodology does not discuss differences between feedstock types. Projects are only allowed to use "sustainable biomass", which is defined in the methodology as biomass **that fits the sustainability criteria set out in the EU RED II Directive or other similar regulations** if the project is outside the jurisdiction of RED II. Therefore, GHG accounting is carried differently for primary biomass and residue and EfW activities are allowed. Furthermore, emissions from biomass are only included if it is purpose grown for BECCS. [SATISFACTORY]
Feedstock production	Measurement: Field emissions	• Although the standard does not mention field emissions by name, it requires cradle-to-gate emissions accounting for sourcing biomass (only if purpose grown for BECCS) according to requirements of the EU RED II Directive, which includes field emissions. [SATISFACTORY]
Co-products	Methodology: Co-products	• Co-products are not accounted for in the methodology as these are (implicitly) assumed to be unchanged compared to the operations without carbon capture. [NEUTRAL]
General	Definition of (net) removals	• The definition of net carbon removals in the methodology does not include accounting of potential emissions reductions that may be achieved through utilisation of BECCS products, for example through replacing fossil-based power with electricity from BECCS. [SATISFACTORY]

Note: The table above excludes the CO_2 transport and storage sections, which are common with the DACCS section.

Puro Earth's approach to certifying biochar

Biochar

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: Material inputs	• The standard states that a life cycle assessment should be used for biomass production and supply to the biochar site. For biomass production, GHG emissions arising from all activities in the biomass cultivation and harvesting process should be included, such as the use of machinery and fuel, production of fertilisers, and emissions from soils following fertiliser use. [SAFTISFACTORY)
Feedstock production	Measurement: Quantifying counterfactual case and indirect land use change emissions	• Puro Earth allows and refers to the positive list of feedstocks supplied by the European Biochar Certificate[1] (which is reviewed later in this report) as well as an IPCC biochar methodology report[2]. The list includes primary (main crop) and secondary (residues/waste) feedstocks. The standard includes direct land use change emissions and accepts modelled values. However, indirect land use change (iLUC) emissions are not addressed, which is a concern for primary biomass. [NEEDS IMPROVEMENT]
Feedstock production	Methodology: Field emissions	• No physical measurements of field emissions are required under the standard. The standard specifies that GHG emissions arising from the production of fertilisers and emissions from soils following fertiliser use should be included in the life cycle analysis. [NEUTRAL] • Emissions from the decay of feedstock during storage are excluded. [NEUTRAL]
Production process	Methodology: Co-products	• The standard specifies that if the co-products represent high-value products or a large share of the initial biomass energy content, then an energy allocation must be applied, with explanation of the allocation factors included in the LCA provided. If the co-products are not deemed an important product, then all of the burdens are allocated to the biochar production (an allocation factor of 100%) and excess co-product is considered as zero emission (allocation factor of 0%). [NEUTRAL]
Other impacts	Methodology: Co-benefits	• Co-benefits are not included in the standard [NEUTRAL]

Biochar decomposition	Measurement: permanence	• The permanence factor calculated is based on:
		  • Soil temperature values from literature or national statistical offices.
		  • The molar hydrogen to organic carbon ratio which must be determined by laboratory analyses of produced biochar with a representative sampling methodology. [SATISFACTORY]
		• Proof that the end-use of the product does not result in reversal of the removal is required. This could be offtake agreements or documentation of the sale or shipment of the biochar indicating the intended use. However, projects are not required to use more rigorous tracking systems under the standard, such as QR codes or other tracking software. [NEEDS IMPROVEMENT]

1. LINK 2. LINK

Puro Earth’s approach to certifying ERW

ERW

Additional information: Puro Earth claims to have created the first crediting system for ERW but has not issued any credits for ERW to date. ERW is at a low TRL compared to other technologies in this study and Puro Earth notes that further model validation is in progress as new data become available.

Process	Uncertainty Type	Approach of the methodology

Weathering	Measurement: Proportion of bicarbonate ions from weathering process contributing to ocean alkalinity and those to carbonate precipitation	• For removal certificates to be issued, evidence in the form of in-field measurements quantifying the amount of CO_2 sequestered must be provided. These measurements must continue throughout the lifetime of the project on at least an annual basis. Parameters required to calculate the amount of CO_2 sequestered are not specified (although some are recommended). However, it is specified that the project must be able to meter, quantify and keep records of their chosen parameters and be available for audit purposes.
		• The amount of CO_2 sequestered must be simulated initially (before application of the crushed rock), using soil and climate conditions specific to the application site. These simulations must be updated alongside on-site monitoring and measurement of the weathering reactions. A life cycle assessment of the activity must also be provided, according to ISO 14040/44 guidelines.
		• To support the simulation, the project must:
		  ○ Conduct a geochemical assay detailing the composition of the crushed rock before application to site
		  ○ Conduct a soil analysis at the application site before the application of the crushed rock to establish the baseline.
		  ○ Provide laboratory results and/or in-field measurements to provide other project-specific parameters
		• Puro provides suggestions for properties that would ideally be included in a project’s simulation model. However, it is noted that it is unlikely that a model would explicitly include every single suggestion. This list includes the relevant processes discussed in task 2.
		• Whilst the above lays out a good foundation in theory, the standard does not turn its suggestions into requirements as ERW modelling is still an ongoing area of research. The does not permit issuing certificates based on modelling results alone and in-field measurements are another ongoing area of research. Therefore, it is difficult to make a judgement on the level of confidence provided by this standard in CO_2 removals through ERW. [NEEDS IMPROVEMENT]

Additional sources of leakage	Method: Leakage via outgassing from effluent	• It is proposed that degassing is included in the modelling of the ERW system [SATISFACTORY IF ENFORCED]
Full chain	Method: Counterfactual	• As described above, the standard requires soil analysis at the application site before project activities commence to establish the baseline. This includes pH, moisture content and any other parameters required for the simulation model. [SATISFACTORY IF ENFORCED]
Other impacts	Method: Co-benefits	• Co-benefits of ERW, such as improved soil quality, are not included. [NEUTRAL]

Puro Earth's approach to certifying carbon negative building materials

Buildings

Additional information: Puro Earth's methodology for carbonated materials was updated in June 2023 to cover general carbonation activities that go beyond those resulting in carbonated building materials, such as carbonation of incinerator ashes, slags, and mine tailings. The update also includes a new baseline calculation to account for natural CO2 removal that would have been achieved in 50 years if the project activities did not happen. Projects are not eligible to issue credits under this methodology if baseline sequestration amount is found to be >50% of the total removals achieved by the project.

Process	Uncertainty Type	Approach of the methodology
CO_2 mineralisation (mixing / curing)	Measurement : Materials input	• The methodology requires all raw materials (e.g., sand, gravel, binder, CO_2, water, slag) to be **"sustainably sourced and sourced in accordance with local regulations"** but does not explain how this is defined or ensured, beyond presenting relevant permits to Auditors. [NEUTRAL] • Emissions associated with the material inputs must be accounted for using emissions factors, which are demonstrated through a product LCA or environment Product declarations (EPD). The methodology recommends applying the "cut-off approach" to accounting for-benefits from using recycled materials (wastes), meaning recycled materials leave the system boundaries burden free. [SATISFACTORY]
CO_2 mineralisation (mixing / curing)	Measurement : Mass of CO_2 captured	• CO_2 storage is quantified by multiplying the amount of building material produced with a factor representing CO_2 sequestration per tonne of product at the factory gate. This factor must be based on measurements (laboratory results need to be verified) or "other scientifically sound methods verified by a qualified third-party auditor". The secondary CO_2 capture processes (capture through concrete curing) is included in this factor. [SATISFACTORY]. However, there are no further elaborations on some of the aspects of calculating the carbon sequestration factor, such as its required accuracy, frequency of measurements, if it should be estimated for different end use cases and if it should be calculated for different product lines / batches. [NEEDS IMPROVEMENT] • The methodology does not mention other potentially more practical methods to estimate CO_2 capture, such as measuring the difference between CO_2 incoming and leaving the system in activities that inject CO_2 to materials. [NEUTRAL]
CO_2 storage in buildings	Methodology: Long-term fate of mineralised CO_2	• The methodology only adopts a cradle-to-gate LCA boundary, therefore distribution, use phase and end-of-life of the carbonated material are excluded from the scope. This is partially justified by the low risk of reversal of removals once carbonation is achieved. These excluded emissions are likely to be the same in the baseline scenarios, where end products are regular building materials. [SATISFACTORY] However, if the end product does not replace an existing product, distribution and use-phase emissions would be missed by the methodology. [NEEDS IMPROVEMENT] • CO_2 Removal Suppliers are required to provide (1) statements of end use, which specifies intended use of the material and storage conditions; (2) a risk assessment and mitigation plan, which includes risks related to exposure to high temperature / acidity, major changes in storage conditions, and change in end uses (destruction, repurposing, etc.); (3) a long-term storage plan, which specifies how long term (100 years) permanence of removals will be achieved if the Supplier ceases to exist, storage site ownership changes or the storage site is destroyed. In general, carbonated materials are not allowed to be used in cases with a risk of exposure to conditions that can cause reversals. [SATISFACTORY]

Note: The table above excludes the key uncertainties relating to CO_2 capture, which are common with the DACCS and BECCS sections.

Expanding standards to new GGR technologies – Puro Earth

DACCS	Already covered ✓	ERW	Already covered ✓
BECCS	Already covered ✓	Buildings	Already covered ✓
Biochar	Already covered ✓	Oceans	Developing a new ocean removals methodology is **expected to be significantly challenging**. • Some existing provisions may be transposed to ocean GGR methodologies (i.e., LCA impacts of energy consumption, geologic CO_2 storage, etc), but new provisions are needed to cover other aspects (tracking DIC storage, air-sea gas exchange, monitoring of the carbonate buffering system, alkaline seawater dispersal, etc). • The required continuous monitoring of carbon sequestration in the ERW methodology could be problematic to ocean removals if applied. • However, ERW coverage by Puro Earth could be best placed (when compared to other technologies) to facilitate the adoption of methodologies for ocean removals, as both ERW and ocean removals involve air-sea gas exchange and DIC storage.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: Verra – VCS (1/2)

Biochar Buildings

General description	
Description and classification	• The Verified Carbon Standard (VCS) Program is administered by Verra. It issues Verified Carbon Units (VCUs) with one VCU representing one metric tonne of carbon dioxide reduced or removed from the atmosphere. • **Classification**: General standard for carbon reduction and removals with technology specific methodologies. Verra recently announced its plans to update the program to enable differentiation between reduction credits and removal credits in mid-2023[1]. • **Background**: In 2006, Climate Wedge and Cheyne Capital transferred Version 1 of the VCS and initial sponsor capital to The Climate Group, International Emissions Trading Association (IETA), and World Economic Forum for them to establish a team to work on future standards. Version 1 of the VCS was officially released in March 2006. The aim was to establish rules and requirements to enable the validation of GHG projects and the verification of GHG emission reductions and removals to be used in voluntary and compliance markets. • The VCS is a global program.
GGR coverage	• The VCS covers biochar and carbon negative concrete. Verra is the standard setter for the CCS+ initiative which will be reviewed separately. • The VCS also certifies nature-based removals such as improved agricultural management practices and afforestation.
Governance structure	• Verra is an American non-profit corporation incorporated as an NGO in 2009. It changed its name from Verified Carbon Standard to Verra in 2018. • The strategic direction of Verra is set by Verra's board of directors who also hold all voting power in the organisation. Advisory groups and committees are convened to guide on programs or specific aspects of work such as digital MRV processes[2]. • **Methodology development** – Stakeholders may submit ideas for methodologies which are reviewed by Verra. A developer (either third-party or a consultant hired by Verra) develops the methodology and produces a draft version reviewed by Verra. A public stakeholder consultation is conducted and an accredited validation/verification body (VVB) assesses the methodology. Verra reviews the methodology and VVB assessment report and determines if the methodology can be approved. An independent scientific advisory board does not appear to be required in the process. Ideas for major and minor methodology revisions can be submitted to Verra using a provided template. Verra periodically reviews VCS methodologies, at least once every five years.
Information rights	Verra owns the IP rights. Third-parties may use the Verra and VCS trademarks with no fee, but prior approval from Verra is required[3].
Number of projects / credits	As of 23rd May 2023, 1,619 projects have been issued VCUs totalling 1.1 billion. Only one project has been registered under the CO_2 utilisation in concrete methodology in March 2023, however another five are under development/validation. There are no projects in the registry under the biochar methodology.
Sustainability requirements	All projects must demonstrate how project activities contribute to the UN Sustainable Development Goals. Demonstration of contribution to at least three SDGs is required by the end of the first monitoring period and in each subsequent monitoring period. Under the biochar methodology, biochar producers must have a health and safety program to protect workers from airborne pollutants and other hazards. Feedstocks must meet additional sustainability criteria depending on the type.
Key documents	• Methodology Development and Review Process v4.2– LINK • Biochar methodology – LINK • Program Guide v4.3 – LINK • CO_2 Utilisation in Concrete methodology – LINK • VCS Standard v4.4 – LINK

1. LINK 2. LINK 3. LINK

Overview: Verra – VCS (1/2)

Biochar Buildings

MRV specifics	
MRV and accounting basics	**Baselines** • The method for determining the baseline is technology specific. Baseline projection updates are only required for certain project types, and not in the case of biochar or CO_2 utilisation in concrete. **Additionality** • Some demonstration of additionality is required for project activities. The details and extent of the demonstration are tech-specific. However, all projects must **demonstrate "regulatory surplus"** at validation and each renewal of the crediting period. This means the project activities **must not be mandated by any law or regulatory framework**. • For biochar and CO_2 utilisation in concrete, beyond the regulatory surplus requirements, the eligibility criteria are used to exclude projects which are not additional. **Permanence** • Buffer pools exist for AFOLU and geological carbon storage projects. A non-permanence report is prepared by the project during the validation and verification stages and a Non-Permanence tool developed by Verra is also applied. Biochar and CO_2 utilisation in concrete are not included in these categories and so there are no buffer pools or non-permanence reports required. • Permanence factors are used for biochar applications to soil. • There do not appear to be requirements around transfer of liability to the government.
Verification and crediting	• **Verification –** Conducted by accredited third-party validation/verification bodies. Site visits are required for validation, as well as certain verification milestones, such as the first verification of the project after validation. • The parameters required for validation and ongoing monitoring are laid out in the methodology, alongside appropriate measurement methods, sources of data, frequency of data and the quality assurance/control procedure. • **Crediting** – Projects may receive VCUs for the length of the project crediting period. The crediting period is renewed periodically to ensure changes to the baseline and regulation are taken into consideration. The period may either be seven years (twice renewable for a total of up to 21 years) or ten years fixed; geologic carbon storage and some nature-based solutions have different crediting periods. Projects and credits are available in a public registry. VCUs are issued to registry account holders listed on the Verra Registry, and ownership of VCUs can only be transferred between registry account holders. They cannot be transferred to other databases or traded as paper certificates, nor are they suitable investments for individuals
Treatment of uncertainty	• Discount factors are occasionally used but are technology specific and are not used in all methodologies.

Verra – VCS' approach to certifying biochar

Biochar

Additional information: Verra's biochar methodology takes a conservative approach by excluding uncertain elements of biochar projects. For example, only allowing waste biomass as a feedstock. The standard also differentiates between low and high technology production processes, as less advanced facilities may not have the same controls as other production systems.

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: Material inputs	• Biomass cultivation processes are not included as only biogenic waste biomass is eligible under the standard (EfW activities are covered). This is defined as the biomass, by-products, residues and waste streams from agriculture, forestry and related industries, recycling economy, animal manure, food processing and others. "Purpose-grown" feedstocks are not allowed. [NEUTRAL]
Feedstock production	Measurement: Quantifying counterfactual case and indirect land use change emissions	• The counterfactual case is pre-defined in the eligibility criteria of the methodology; feedstock must have otherwise been left to decay or combusted for purposes other than energy production. This may be evidenced either with historical management plans for the areas where the biomass is sourced from, consultation and signed attestation from the supplier during that period, or demonstrate abundant surplus (of at least 25%) of the biomass residues in the project region which is not utilised [SATISFACTORY] • As only waste biomass is eligible and biomass cultivation falls outside of the system boundary, direct and indirect land use change emissions from feedstock production are not included. [SATISFACTORY]
Feedstock production	Methodology: Field emissions	• CO_2, CH_4, and N_2O emissions are all excluded from the project boundary as only waste biomass is eligible under the standard. [NEUTRAL] • Emissions from the decay of feedstock during storage are excluded. [NEUTRAL]
Production process	Methodology: Co-products	• Co-products are considered to be outside of the methodology scope[1]. Therefore, all emissions associated with the pyrolysis facility are allocated to the biochar. [NEUTRAL]
Other impacts	Methodology: Co-benefits	• Co-benefits are not included in the biochar carbon removals methodology. There is a separate methodology for increasing soil organic carbon (SOC) storage, "Methodology for Improved Agricultural Land Management" and the application of biochar is an eligible activity under this methodology. However, the two cannot be combined if the biochar is applied to the same soil. Verra deems it too difficult to differentiate biochar carbon from other forms of soil carbon when quantifying SOC stock changes in this instance[2]. [NEUTRAL]
Biochar decomposition	Measurement: permanence	• Default permanence values based on biochar production temperature are provided from literature; project developers must report the temperature used for biochar production to justify the decay rate used. Soil temperature is not factored in; the default values are deemed conservative as they are calculated based on average soil temperature of 20°C which is 10°C hotter than the average land surface temperature and decomposition increases with temperature[3]. However, Verra is a global programme, and the methodology could be implemented at higher soil temperatures which would lead to a higher decay rate than that calculated from Verra's standard. [NEEDS IMPROVEMENT] • The final location of the site where the biochar is applied must be known and the project developer must verify that the application took place. For example, tracking records or QR codes. [SATISFACTORY IF ENFORCED]

1. LINK 2. LINK 3. LINK

Verra – VCS' approach to certifying carbon negative building materials

Buildings

Additional information: The VCS addresses one type of carbon negative building materials which is CO2 utilisation in concrete. The methodology is for utilisation of any waste CO2 which would have otherwise been emitted into the atmosphere. CO2 from direct air capture (DAC) is also allowed. CO2 from either DAC or biogenic sources could make the concrete carbon negative.

Process	Uncertainty Type	Approach of the methodology
CO_2 capture	Methodology: Energy Input	• The standard allows for national/regional average emissions intensity factors for grid electricity to be used or the UN Clean Development Mechanism's "Tool to calculate the emission factor for an electricity system.[1]" The monitoring requirements specify the quantity and emissions intensity of electricity from the grid; it is unclear if this can be adapted if the project generates its own electricity (e.g. on-site solar). • The emissions intensity of the electricity must be updated annually but no other temporal aspect of the emissions intensity is included, nor is there an assessment of the impact of additional grid electricity demand on the wider system. [NEEDS IMPROVEMENT]
CO_2 mineralisation (mixing / curing)	Measurement: Materials input	• Three options are provided to estimate the emissions factor of the Portland cement in the concrete. In order of stated preference: 1. Plant-specific data for total energy and fuel use. To be used when source of cement is known and production is co-located with concrete production. Does not include lifecycle emissions of the material inputs (e.g. aggregates). [NEEDS IMPROVEMENT] 2. Environmental Product Declarations (EPDs). A comprehensive summary report of environmental impacts of material production based on LCA verified by a third-party. EPDs are typically cradle-to-grave (including extraction of raw materials) which results in a higher emissions factor than options 1 or 3. [SATISFACTORY] 3. Regional factors for the ratio of clinker to cement and the emissions factor of the clinker are used to calculate the emissions factor of cement. Does not include lifecycle emissions of the material inputs. [NEEDS IMPROVEMENT]
CO_2 mineralisation (mixing / curing)	Measurement: Mass of CO_2 captured	• Secondary CO_2 capture processes are not included in the methodology (see Task 2 report for further detail on the secondary processes). This is likely because the secondary CO_2 capture processes are expected to happen in the baseline as well. [NEUTRAL] • The methodology provides two options for determining the amount of CO_2 captured and mineralised in the concrete: 1. Testing concrete samples with a carbon analyser which determines the level of embedded carbon. This can then be contrasted to the results from the baseline sample to give the additional CO_2 stored. [SATISFACTORY] 2. If a manufacturer is producing too many different mix designs (proportions of cement, sand and aggregates), testing may not be feasible. In this case, projects may use the measured amount of CO_2 injected into the projects' process multiplied by a conservative default value provided by Verra for the efficiency of CO_2 mineralisation may be used. This value is currently 60%. [SATISFACTORY] For both options, the measurement methods and frequency of measurement are specified. [SATISFACTORY]
CO_2 storage in buildings	Methodology: Long-term fate of mineralised CO_2	• No sources of leakage were identified in the methodology and there is no requirement to track the long-term fate of the produced concrete. Projects are only required to monitor the production and sale of concrete produced, with sales records used to ensue that the produced concrete is entering the market and displacing conventional concrete. [NEEDS IMPROVEMENT]

Note: The table above excludes the key uncertainties relating to CO_2 capture (biogenic), which are common with the biochar section. 1.LINK

Expanding standards to new GGR technologies – Verra VCS

DACCS

Developing a new DACCS methodology is **not expected to be challenging** because:

- Verra is developing a CCS methodology as part of the CCS+ initiative and already has requirements for geological storage.
- Providing the CCS+ methodology is adequate once published, provisions relating to storage of CO_2 can directly follow the CCS+ initiative
- Other aspects of a DACCS methodology, such as accounting for energy / chemical consumption and transportation of CO_2 are relatively straightforward subjects.

ERW

Developing a new methodology for enhanced rock weathering is **expected to be significantly challenging** because:

- Existing methodologies do not have many common provisions with ERW activities.
- ERW still carries inherent uncertainties, which require continued experimentation and research to resolve.
- MRV protocols must rely on modelling to a degree, alongside additional field testing. To date, no ERW models have been fully validated.

BECCS

Developing a new BECCS methodology is **not expected to be challenging** because:

- As with DACCS, providing the CCS+ methodology is adequate once published, provisions relating to storage of CO2 can directly follow the CCS+ initiative
- Rules around biomass supply may follow the biochar methodology or other nature-based Verra methodologies.
- Remaining aspects, such as CO_2 transportation and treatment of co-products are likely to be resolved relatively easily due to precedence set in other sectors.

Buildings

Already covered ✓

Biochar

Already covered ✓

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging**

- A baseline assessment for ocean removals would likely be required, as this would provide a foundation from which to base the significant amount of expected modelling from.
- The buffer pool of credits as a mechanism for non-permanence could be explored in ocean removals.
- The third-party verifiers requirement could be used for ocean removals, but there is a noted absence of mature verifiers in this space.
- Discounts and the flexible crediting period could both be an opportunity to update credit generation potential based on new available ocean removal monitoring and modelling techniques.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: Gold Standard (1/2)

BECCS Buildings

General description	
Description and classification	• **The Gold Standard (GS)** is non-profit organisation responsible from running **The Gold Standard for Global Goals** (GS4GG) carbon crediting program. It issues credits called **Verified Emission Reduction (VER)**, which are mostly used in the global voluntary markets and labels Certified Emissions Reductions (CERs) issued under the Clean Development Mechanism (CDM), where they meet Gold Standard's additional requirements. The GS also offers other credits and impact statements based on Sustainable Development Goals (SDGs), such as renewable energy deployment, water benefits, gender equality, improved health, and black carbon reductions. • **Classification**: The GS4GG is a general standard to certify both emissions reductions and GGRs. • **Background**: The GS was initiated in 2003 by the World Wide Fund for Nature (WWF), South-South-North, and Helio International to certify activities under the Clean Development Mechanism (CDM). The first voluntary GS standard was released in 2006. The GS was revised in 2017 to its current form (GS4GG), which incorporates contributions to SDGs in its core principles, requiring all projects to have at least two SDG contributions besides GHG reduction / removal.
GGR coverage	As of May 2023, the GS4GG has 29 active methodologies, most of which are used to assess emissions reductions or other SDG benefits. Only three existing methodologies certify GGRs through afforestation/reforestation, soil carbon storage, and carbon negative building materials, through accelerated carbonation of concrete aggregates. Furthermore, there is currently an active consultation on a BECCS methodology for biomass fermentation combined with CO_2 pipeline transport and storage in geologic formations.
Governance structure	• **The Gold Standard a not-for-profit organisation** headquartered in Geneva, Switzerland. • Financial and strategic oversight is carried by the Foundation Board, which consists of members from NGOs, private and public sectors. The Gold Standard Secretariat is responsible for setting the standards and running the programme, including innovation and thought leadership. The Technical Governance Committee (TGC) provides strategic input and oversight of standards. Technical Advisory Sub-Committees (TAC) consist of subject matter experts and provide input for specific objectives as well as approval of new requirements, methodologies and some deviation requests. • **Methodology development** – The GS4GG accepts applications for new methodologies to expand coverage of technologies or sectors of the standard. Developers must first submit a concept note for approval by the TAC. Following submission of the full draft methodology, two internal and one external reviewers are selected to provide up to three rounds of feedback. The proposal then goes through a 30-day public consultation period and the final approval is given by the TAC.
Information rights	GS considers its methodologies and other requirements to be public goods. Currently some GS4GG credits meeting eligibility criteria are accepted by South Africa's and Colombia's carbon tax programmes as well as CORSIA. Similarly, the UK Government may be able to endorse GS4GG credits for its own programmes.
Number of projects / credits	As of 25th May 2023, GS has issued 229 million credits (VERs) in addition to labelled CERs issued under the CDM. Together, these come from more than 2900 projects registered in around 100 countries. A total of 142 million VERs have been retired in the same period.
Sustainability requirements	GS4GG projects should **"not undermine or conflict with any national, sub-national or local regulations or guidance relevant to project activity".** GS4GG also requires all projects to contribute to at least two other SDGs, besides climate impact, on a continuous and measurable manner. All projects are required to go through a safeguarding principles assessment procedure (Link) where they must identify potential social, environmental, economic risks and adopt mitigation strategies to minimise risks across core principles identified by GS4GG.
Key documents	• Principles and Requirements – Link • Validation and Verification Standard – Link • Impact Quantification Methodologies – Link • Methodology for concrete carbonation – Link • Proposal for a BECCS fermentation methodology – Link

Overview: Gold Standard (2/2)

BECCS Buildings

MRV specifics	
MRV and accounting basics	**Baselines** • The baseline for BECCS and carbon negative buildings materials are defined as the CO_2 emissions that would have been emitted (or not captured) in the absence of the project. For BECCS, this is a dynamic baseline and is calculated from the direct measurement of CO_2 injections . For concrete mineralisation this is calculated ex-ante (based on particle size and capture factors) or ex-post (measuring difference of CO_2 in the inlet and outlet of the carbonation plant). **Additionality** • All projects are required to demonstrate additionality through tools approved by the UNFCCC or Gold Standard, such as CDM's "Combined tool to identify the baseline and demonstrate additionality". These assess additionality based on a combination of **regulatory surplus**, barrier analysis, and financial additionality. • For concrete mineralisation, projects are not allowed to increase CO_2 production levels above the baseline levels and result in final products that are functionally the same as alternatives. • To avoid double counting project developers are required to communicate with all project proponents in writing that they are claiming the carbon removal rights of the activities. **Permanence** • For BECCS projects, a percentage of credits must be deposited into a buffer pool to cover leakage risk. The exact percentage depends on numerous project specific factors including regulatory risk, political risk, resource tenure risk, land tenure risk, storage site closure risk, and storage site design risk. Activities require continuous monitoring at the storage site. • For concrete mineralisation, resulting $CaCO_3$ is not allowed to be used in applications where it is thermally or chemically decomposed (e.g., extraction of mineral via solvents). It is assumed that the application of the resulting $CaCO_3$ as a filler material for the construction sector results in permanent storage. End uses in other sectors may be allowed if permanent storage is proven. On site monitoring of end use is not required.
Verification and crediting	• New projects wishing to register with GS4GG must first submit and get approval on a draft project plan. Project proponents must then contract an approved independent validation and verification body (VVB) to validate the full project design and monitoring plans, including an estimation of theoretical GGR levels. A stakeholder consultation must also be completed concurrently. Following Project Design Certification by GS4GG, projects may initiate Performance Certification (verification) at intervals of their choosing. Credits can only be issued after GS4GG reviews and approves the verification and monitoring reports forwarded by VVBs. • VVBs must have be accredited to ISO 14065 (under the ANSI-GS Accreditation Program), UNFCCC-CDM Accreditation (AIE or DOE status) or ASI (FSC Certification Body status) to be approved by GS. • Project Design Certifications typically last for 5-years, but project proponents may apply for re-validation to certification extend by 5-years. The BECCS methodology proposes to allow 5 such extensions for a total of 30 years of crediting. This period is longer for nature-based solutions, including afforestation / reforestation. • A performance review (including a site visit) must be conducted by VVBs before each round of credit issuance. • After the preliminary review conducted by GS, all projects are publicly listed on the Gold Standard Impact Registry, along with their key documentation and credits issued.
Treatment of uncertainty	In general, GS4GG encourages using conservative estimations to reduce uncertainties then apply discount rates to account for remaining uncertainties. Uncertainty is defined as the standard deviation around the mean at the 90% level of confidence. If uncertainties are above 20% for input parameters, significant discounts (up to 50%) start to apply to number of credits issued. Individual methodologies for GGRs do not contain additional provisions on uncertainties, except for BECCS, where any CO_2 leakage must be estimated at an uncertainty of less than ±7.5%. If uncertainty is estimated to be higher, the leakage volume is assumed to be increased by the uncertainty rate.

Gold Standard's approach to certifying BECCS

BECCS

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: All feedstock components	• The methodology requires biomass feedstocks to be "renewable", which is demonstrated through either (a) evidence that the fermentation process or its products are registered / **certified by regional regulations** (e.g., US EPA Renewable Fuel Standard or EU RED II Directive) that define acceptable renewable energy sources or (b) meeting the renewable biomass definition in CDM EB 23 Report Annex 18. EfW activities are allowed. [SATISFACTORY] • Emissions and leakage (knock-on effects) from biomass is considered to be zero unless projects are either greenfield or have carbon credits as their sole income. [SATISFACTORY] If required, these emissions are calculated based on CDM Tool 16: project and leakage emissions from biomass. The tool allows using of default parameters (where possible), but also accepts project specific parameters obtained from measurements. [SATISFACTORY] • ILUC emissions are only accounted for feedstocks that may cause leakage (at risk of knock-on effects across different end-users), which are defined as projects that meet the "renewable biomass" definition through option b above. [NEUTRAL] • Carbon payback time is not accounted for in the methodology.
Feedstock production	Methodology: Material inputs	The methodology only allows using biomass that is deemed "renewable" according to the criteria listed above. It does not directly make a distinction between waste and primary biomass, however, the CDM Tool 16 makes distinctions between residues and primary biomass. [SATISFACTORY]
Feedstock production	Measurement: Field emissions	According to CDM Tool 16, emissions from biomass cultivation include field emissions (soil organic carbon and nitrous oxide), which can be calculated using default values, although project developers are encourage to use alternative measurement approaches. [SATISFACTORY]
Co-products	Methodology: Co-products	Co-products are not accounted for in the methodology, however, this is not expected to be an issue for retrofit projects, since co-products volumes are not expected to be different than baselines. [NEUTRAL]
General	Definition of (net) removals	The methodology does not include any end use substitution (e.g. fossil fuels being replaced by biofuels) in the calculation of removals. In retrofit projects, the project activity would not have an effect on co-products since the same amount of fermentation happens in the baseline. [SATISFACTORY]
CO_2 transport and storage	Methodology: Energy Input	The methodology accounts for emissions from construction of infrastructure and energy demand for transport and storage of CO_2 [SATISFACTORY], however, there is no guidance as to how to assess emissions for other transport types besides pipelines . [NEEDS IMPROVEMENT]
Geological storage	Measurement: CO_2 migration, trapping and leakage	• The methodology sets out minimum requirements for selection and characterisation of reservoirs, injection well design and construction, storage site monitoring and closure. These are based on US EPA Underground Injection Control Program Class VI Guidance and ISO 27914. The methodology is designed to be able to be **compatible with local CCS regulations** meeting these requirements. [SATISFACTORY] • A robust reservoir model is required to be developed and updated throughout the project lifecycle, to incorporate data obtained through physical measurements. A project specific monitoring program should be developed according to risk factors and leakage pathways identified. [SATISFACTORY] • Minimum site closure regulatory requirements include clarifying the entity retaining long-term liability, conditions for future liability transfers and provisions for remediation in case of leakage. Post-injection monitoring must continue for at least 10-years with annual reporting. [SATISFACTORY] • Regulations / guidance do not reference storage via rapid mineralisation, which can be assumed to be ineligible for certification. [NEUTRAL]

Gold Standard's approach to certifying carbon negative building materials

Buildings

Additional information: Gold Standard's methodology only applies to new or retrofit carbonation plants that store additional CO2 in concrete aggregate, which is a by-product of concrete demolition. The methodology applies to both direct carbonation (exposure of fine aggregates to high CO2 concentrations) and indirect carbonation (carbonation after cement phases are extracted by a solvent). Currently projects using CO2 only from air or biogenic sources are allowed to be certified, however, the methodology explicitly suggests that mineralisation of fossil-based CO2 may be allowed, with prior approval and relevant changes made. Presumably if this was allowed, the project would not be allowed to label the credits as GGR.

Process	Uncertainty Type	Approach of the methodology
CO_2 capture (atmospheric)	Methodology: Energy Input	• The methodology accounts for the emissions associated with energy use for CO_2 capture processes. These are calculated from energy use and associated emissions factors based on average grid carbon intensity or the most recent version of IPCC Guidelines for National GHG Inventories. [SATISFACTORY] • Wider system impacts of electricity use are not accounted in the methodology. [NEEDS IMPROVEMENT] • The methodology does not include specific provisions about treatment of waste heat. [NEUTRAL]
CO_2 mineralisation (mixing / curing)	Measurement: Materials input	• Carbonation of concrete aggregates is not expected to require any additional material inputs, besides consumption of solvents if the indirect carbonation route is selected. The methodology accounts for emissions from solvent replenishment (embedded emissions) and electricity / fuel consumption associated with pre-treatment of concrete aggregates (if needed), carbonation, CO_2 capture, CO_2 treatment, and transport all of materials (CO_2, concrete aggregate, etc.) inside the project boundary. End products, such as carbonated aggregates, may be used downstream for producing construction materials, however, those processes are not in the scope of this methodology. [SATISFACTORY]
CO_2 mineralisation (mixing / curing)	Measurement: Mass of CO_2 captured	• The methodology does not account for secondary CO_2 capture processes (from concrete curing) directly. However, if CO_2 capture volumes are chosen to be quantified through the ex-ante calculation method, which uses CO_2 capture factors (based on experimentation or literature) for different aggregate grain sizes, secondary impact may be accounted for in capture factors used. Since this methodology only applies to carbonation of concrete aggregates, it may be assumed that carbonation will be relatively maximised (due to small grain sizes) after the primary processes, so secondary impacts may be deemed negligible. [SATISFACTORY]
CO_2 storage in buildings	Methodology: Long-term fate of mineralised CO_2	• The methodology requires demonstration of end use of products (carbonated aggregates or $CaCO_3$ + regenerated sand), through sales records, invoices, etc. Project developers must report the general types of activities that the products will be used in (e.g., road construction, concrete structures, etc.). $CaCO_3$ is only allowed to be used in the construction sector (automatically assumed permanent storage) or other applications that will not release the carbon (which needs verification by VVBs). It is assumed that the use of carbonated aggregates in the construction sector results in permanent removals. [SATISFACTORY]

Note: The table above excludes the key uncertainties relating to CO_2 capture (biogenic), which are common with the BECCS section.

Expanding standards to new GGR technologies – Gold Standard

DACCS

Developing a new DACCS methodology or expanding the coverage of the proposed BECCS methodology to cover DACCS is **not expected to be challenging** because:

- The BECCS methodology already has many provisions – around accounting for project emissions, CO_2 transport and CO_2 storage – that would apply to DACCS as well.
- Unique provisions for DACCS, such as proving the source of CO_2, are well understood and practiced in the MRV space.

ERW

Developing a new methodology for enhanced rock weathering is **expected to be significantly challenging** because:

- Existing methodologies do not have many common provisions with ERW activities.
- ERW still carries inherent uncertainties, which require continued experimentation and research to resolve.
- MRV protocols must rely on modelling to a degree, alongside additional field testing. To date, no ERW models have been fully validated.

BECCS

The scope of the proposed BECCS methodology can **easily be expanded** to include non-fermentation applications and CO_2 transport by means other than pipelines because:

- These changes adhere to the general principles of the methodology and only require small updates to the text, the equations, and the parameters monitored.

Buildings

The scope of the existing methodology on carbon negative building materials can **easily be expanded** to include carbonation of materials other than concrete aggregates (recycled concrete) because:

- Such an expansion would only require minor changes in the text and provisions around establishing baselines, additionality, and monitoring of product end use.

Biochar

Developing a biochar methodology under GS is **expected to be moderately challenging** because:

- Existing methodologies can help with drafting the sections on sourcing biomass, accounting for biomass emissions, soil applications of biochar, and accounting for other energy products obtained from pyrolysis.
- However, new provisions would have to be developed to address permanence of removals and accounting for biochar decay.

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging.**

- Requiring ocean removal projects to meet two additional UN SDGs could be an opportunity to manage sustainability impacts.
- There is currently no established baselines for ocean removal projects within the Gold Standard.
- The treatment of uncertainty via credit discounts could be transposed to ocean removal projects to help mitigate against the uncertainty in atmospheric drawdowns and carbonate chemistry effects. This is already present in at least one OAE methodology (Planetary).
- It would have to be determined if verification bodies with the potential to work with ocean removal companies have been/can meet the ISO 14065, UNFCCC-CDM Accreditation or ASI status qualifications.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: American Carbon Registry (1/2)

DACCS BECCS

General description	
Description and classification	• **American Carbon Registry (ACR)** is non-profit organisation running a carbon crediting program (also called ACR) operating in both the voluntary and compliance markets (CORSIA, California Cap-and-Trade, Washington Cap-and-Invest). ACR issues credits, called Emission Reduction Tons (ERTs), in the voluntary market with a global scope. • **Classification**: ACR is a general standard for both emissions reductions and GGRs. • **Background**: ACR was founded in 1996 as the first private voluntary GHG registry in the world. ACR is an enterprise of Winrock International, which is a non-profit organisation named after Winthrop Rockefeller and is operating in the US and internationally. In 2012 ACR was approved to be an Offset Project Registry for California's Cap-and-Trade programme, which was the beginning of ACR's involvement in compliance markets.
GGR coverage	ACR has 15 active methodologies, most of which apply to emissions reductions focusing on non-CO_2 GHGs and land use / forestry. ACR has been certifying some nature-based GGRs through afforestation and ecosystem restoration, but only recently published a specific methodology for certifying carbon capture and storage (CCS). The current CCS methodology covers DACCS, BECCS (no limitations), and other non-GGR CCS using CO_2 for enhanced oil recovery (EOR). However, an update to the methodology – currently under consideration – will expand the scope to other geologic storage options and projects outside of North America.
Governance structure	• ARC is a wholly-owned non-profit subsidiary of Winrock International and is governed by Winrock's Board of the Environmental Resources Trust (ERT). • **Methodology development** – New methodologies or modifications to approved methodologies can be submitted to ACR by any interested party. Methodology developers pay a registration fee and after initial screenings by ACR, proposals are posted for public comments online for at least a period of 30 days. Updated proposals are then sent to independent subject matter experts for peer review. Methodology developers address all comments at all stages, which are published online if the proposal is accepted. The same procedure applies to substantial updates ACR initiates itself. ACR may choose to update methodologies if it becomes aware of substantial change in circumstances. • ARC updates its overall standard at least every 3 years, or sooner if it is made aware of changes in best practices that it deems substantial. Proposed changes are opened for public consultation for 60 days and ARC respond to all comments. ACR may establish Technical Committees on a case-by-case basis to support decision making regarding accepting new methodologies, modifications, project deviation, selection of peer reviewers, etc.
Information rights	ACR and all of their IP is privately owned by Winrock International. Any official future partnership would require bilateral agreements and a likely financial contribution, in line with ACR's relationships with various international and regional compliance programmes.
Number of projects / credits	In 2022, 70 projects issued credits with ARC and as of 20th May 2023 a total of 616 projects were registered in total with ARC. No projects have been registered with ARC under the current CCS methodology.
Sustainability requirements	ACR requires all projects to disclose an environmental and community impact assessment. This includes (1) identification of all risks / impacts, (2) categorization as positive or negative, (3) description of how negative impacts will be reduced, mitigated or compensated, (4) description of which Sustainable Development Goals the positive impacts contribute to and (5) a plan to monitor these risks / impacts. Community based projects are required to provide additional information regarding stakeholder engagement processes, land and resource rights, impact on wellbeing, etc. All projects must follow "do no harm" principles, and CCS projects must submit any environmental impact assessment they undertake **as part of national regulations.**
Key documents	• ACR Standard – Link • ACR Validation and Verification Standard – Link • ACR CCS Methodology v2.0 Draft – Link

Overview: American Carbon Registry (2/2)

DACCS BECCS

MRV specifics	
MRV and accounting basics	**Baselines –** The baseline for DAC is defined as the amount of CO_2 that would remain in the atmosphere in the absence of project activities, which is obtained by directly measuring captured CO_2 volumes. For other CCS projects, baselines may either be calculated in a "projection-based" way (actual CO_2 emissions produced by the activity before the capture process, corrected for any additional CO_2 that may be caused by the capture process) or a "standards-based" way, which is based on the output of the facility multiplied by an appropriate emissions factor. The standard-based approach is used if **there are regulations already limiting allowable emissions** at a certain level (standard / benchmark). **Additionality –** Generally, ACR projects can meet additionality requirements in two ways: 1. A **three-prong test** consisting of **regulatory surplus** (activity not required by existing regulations) AND common practice test (activity not widely adopted) AND at least one of the following barriers: financial, technological or institutional. 2. Exceeding an **approved performance standard** (specific to each methodology). This consists of regulatory surplus AND a performance standard based on either the adoption rates of a particular practice / technology or the performance of the technology based on a GHG benchmark (being significantly better than counterfactuals). • The CCS methodology specifically adopts the second approach and deems all CCS technologies pass the performance threshold since CCS uptake is very low in North America. **Therefore, projects are deemed additional if they are not required by existing regulations.** This regulatory surplus clause must be demonstrated every 10-years to renew the crediting period. **Permanence –** Currently ACR requires Project Proponents of geologic storage activities to contribute 10% of ERTs to a Reserve Account, which is to be used to retire credits in case of leakage. However, since geologic CO_2 storage is generally deemed to be secure, the anticipated updated methodology is set to reduce this buffer pool to 10% of maximum CO_2 volume stored in any single year, instead of 10% of cumulative storage. After the project term, Project Proponents are required to fill a Risk Mitigation Covenant to ensure that ACR would be compensated (financially to cover ACRs costs of sourcing new credits) for any intentional reversals of CO_2 storage. The covenant is deemed cancelled when the CO_2 leakage liability of the storage site eventually transfers to the government under local regulations. At any point Project Proponents may ask to replace these risk mitigation measures by securing an external financial insurance policy that is approved by ACR. CCS projects are required to continue storage site monitoring for at least a period of 5 years after the end of project activities (end of CO_2 injection from the project). If it can be demonstrated that no leakage has occurred during this period and the CO_2 plume has stabilised, monitoring can stop. Otherwise, monitoring period is extended by 2-year increments.
Verification and crediting	• **Crediting** – CCS projects are allowed a crediting period of 10 years, after which Project Proponents may apply for further 10-year extensions by demonstrating compliance and additionality in line with the active CCS methodology of the time. ACR maintains a public registry of all issued and retired credits in its voluntary and compliance markets. Data disclosed include number of credits, serial numbers, dates and key project documentation. Both emissions reductions and removals result in the same type of credit (ERT). • To register a new project, an initial screening by ACR is required. Project Proponents must then contract a Validation / Verification Body (VVB) and obtain a validated GHG Project Plan, a verified monitoring report, a validation report, a verification report, and a verification statement. ARC reviews these documents, registers the project and issues ERTs accordingly. • VVBs are independent third parties, meet requirements of ISO 14065:2013 and are accredited by a body which is a member of the International Accreditation Forum. VVB must submit a conflict of interest form and Project Proponents are required to change their VVBs at least every 5 years. • After project initiation, VVB's must verify project activities at regular intervals before ERTs can be issued. Verification of project outputs are allowed to happen remotely, but field visits are required at a minimum of every 5 years.
Treatment of uncertainty	ACR methodologies require projects to estimate and reduce GHG accounting uncertainties as far as practical. Methodologies based on statistical sampling (for example forestry and land use sectors) have additional provisions around permitted uncertainty levels. According to the CCS methodology all project plans must include a quality assurance and control (QA/QC) plan. All measurement instruments must be calibrated to an accuracy of 5%. The methodology states that the uncertainty levels of CCS processes are all low, assuming that storage site characterisation is done at a sufficient level and the operators are already required (by local regulations) to track and submit detailed logs of all fugitive emissions and venting evets.

ACR's approach to certifying DACCS

DACCS

Process	Uncertainty Type	Approach of the methodology
CO_2 capture	Methodology: Energy Input	• The methodology does not consider the time of use of electricity and relies on annual metered electricity consumption and an associated emissions factor obtained through the US EPA's Emissions & Generation Resource Integrated Database. If possible, average grid emissions are used for the Balancing Authority Area (BAA) the projects falls under. If not possible, state-wide emission factors are also allowed. [NEUTRAL] • If projects receive electricity from other dedicated sources, they are allowed to demonstrate this and use emissions factors associated with the source [SATISFACTORY], however, embedded emissions in materials and land use change effects of additional renewable energy are excluded from the methodology. [NEEDS IMPROVEMENT] • Currently treatment of power procurement agreements (PPAs) under the methodology is not clear, however, the ongoing update to the methodology is expected to introduce a requirement to provide additionality for power procured through PPAs. This is expected allow renewable energy purchases only if the energy output of renewable facilities is improved via project activities, for example through installing battery storage or reducing curtailment. [SATISFACTORY] • The methodology includes a formula to calculate GHG emissions associated with purchased heat, however, it has no specific provisions about using waste heat, meaning that these sources may not be treated as zero emissions. [NEUTRAL]
CO_2 transport and storage	Methodology: Energy Input	• The methodology covers emissions (CO_2, CH_4 and N_2O) from transportation of CO_2 via pipelines, shipping, and other mobile vehicles. These include all fugitive emissions, venting, onsite combustion and electricity / fuel use. If the project uses a common transport network, such as an industrial CCS cluster using a single pipeline, emissions of the whole system is prorated according to the annual proportional use. [SATISFACTORY] • Emissions from CO_2 storage are treated in a similar fashion as transportation with the addition of annual leakage from the site. [SATISFACTORY]
Geological storage	Measurement: CO_2 migration, trapping and leakage	• The MRV requirements for the storage site and operations are **designed to be aligned with the regulatory standards** of the US, Canada, and ISO. This requires project proponents to develop a site specific MRV plan including: developing a flow model to estimate storage space needed, identifying potential leakage pathways and remediation measures, designing a strategy to monitor effective CO_2 retention and quantify leakages. [SATISFACTORY] • Project proponents are required to determine the key parameters (depending on uncertainty and sensitivity analysis) they plan to monitor to determine leakages, potential future leakages and accuracy of the fluid flow modelling. **These must comply, at the minimum, with local regulations.** Project proponents must also set their own allowable limits on measured parameters and investigate /quantify potential leakages if these limits are surpassed. Other aspects of the monitoring strategy, such as monitoring tools and sampling frequency, should depend on the sensitivities of individual parameters to the outcome of simulations. Specific leakage quantification methods are also left to the project proponents, but they should be based on best scientific and engineering practices, conservative estimates, and reservoir specific data. [NEUTRAL] • After the end of injections, the site should be monitored for a minimum period of 5 years. This includes measuring sub-surface pressure to see if it is consistent with modelling or if there is an indication of leakage. If the CO_2 plume is observed to migrate out of the project boundary, the boundary must be redefined and new a new MRV plan is needed to identify new leakage and leakage pathways. If after 5 years, leakage or CO_2 plume migration cannot be overruled, monitoring is extended by 2 years. [SATISFACTORY] • This methodology explicitly excludes rapid CO_2 mineralisation. [NEUTRAL]

ACR's approach to certifying BECCS

BECCS

Additional information: The methodology does not limit the types of BECCS allowed, so it may apply to most BECCS configurations. The proposed methodology treats BECCS plants exactly the same as general CCS plants, except for requiring feedstocks to be "sustainable biomass" (see below). The methodology is primarily designed to estimate biogenic emissions reductions compared to the baseline, rather than quantifying net carbon removals achieved by BECCS plants, which explains exclusion of several types of project emissions associated with biomass cultivation and sourcing, as detailed below.

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: All feedstock components	• The methodology only allows using biomass feedstocks that it deems "sustainable", which are defined as: forestry (slash or waste from forest and shrub/chaparral management and sawmill residue), agriculture (crop residue, manure, and energy crops cultivated on marginal or degraded land), and waste (municipal, landfill gas, and wastewater). Therefore, EfW activities are covered by the methodology. Emissions from feedstock cultivation, transportation or processing are not included in the scope of the methodology, because these are (implicitly) assumed to be the same as the baseline emissions. This assumption may have merit for retrofit projects, but risk missing significant LCA emissions in a new build plant, since the allowable biomass types listed above still have cultivation emissions associated with them. [NEEDS IMPROVEMENT]
Feedstock production	Methodology: Material inputs	• The methodology treats all allowable feedstock types listed above equally, which means that energy crops cultivated on marginal or degraded land is deemed equivalent to other kinds of forestry and waste biomass. Furthermore, there is not a clear definition of what constitutes as "marginal or degraded land". [NEEDS IMPROVEMENT]
Feedstock production	Measurement: Field emissions	• Field emissions are excluded from the scope along with other emissions from feedstock production. [NEEDS IMPROVEMENT]
Co-products	Methodology: Co-products	• Co-products are not accounted for in the methodology as these are assumed to be unchanged compared to the operations without carbon capture. [NEUTRAL]
General	Definition of (net) removals	• The definition of net carbon removal in the methodology does not include accounting of co-products (for example through substitution), which are assumed to be unchanged compared to the operations without carbon capture. [SATISFACTORY]

Note: The table above excludes the CO_2 transport and storage sections, which are common with the DACCS section.

Expanding standards to new GGR technologies – ACR

DACCS

Already covered ✓

ERW

Developing a new methodology for enhanced rock weathering is **expected to be significantly challenging** because:

- Existing methodologies do not have many common provisions with ERW activities.
- ERW still carries inherent uncertainties, which require continued experimentation and research to resolve.
- MRV protocols must rely on modelling to a degree, alongside additional field testing. To date, no ERW models have been fully validated.

BECCS

Already covered ✓

Buildings

Developing a new carbon negative building materials methodology under ACR is **expected to be moderately challenging** because:

- Existing methodologies can help with drafting the sections on obtaining CO_2 from eligible sources, however,
- Original provisions need to be developed regarding accounting and measuring the exact amount of CO_2 stored in products, separation of carbon removals and emission reductions (via reduced cement demand), and tracking end use of building materials.

Biochar

Developing a biochar methodology under ACR is likely to be **expected to be moderately challenging** because:

- Existing methodologies can help with drafting the sections on sourcing biomass, accounting for biomass emissions, soil applications of biochar, and accounting for other energy products obtained from pyrolysis.
- However, new provisions would have to be developed to address permanence of removals and accounting for biochar decay.

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging.**

- The requirements to publish community impact assessments may be challenging for projects which occur farther out in the exclusive economic zone (up to 200 nautical miles).
- The baseline provisions in ACR would be challenging to adapt to ocean removals, as they require direct measurement of removal (challenging with air-sea gas exchange and DIC storage) or established regulations (not present for ocean removals).
- Proving additionality would be challenging via the ACR guidelines.
- The required credit Reserve Account could be transposed to manage leakage or uncertainty risk, especially for DOR projects which would require geological storage, and for the uncertainty of air-sea gas exchange and DIC storage.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: Climate Action Reserve (1/2)

Biochar

General description	
Description and classification	The Climate Action Reserve is an American voluntary program which establishes standards for GHG emissions reduction projects, oversees verification bodies, issues carbon credits and tracks these credits as part of a public registry. The standards are known as protocols and the carbon credits are Climate Reserve Tonnes (CRT). • **Classification**: Technology specific standard and general crediting scheme for carbon reduction and removals. At present, protocols have been developed or are under development for biochar, natural climate solutions, waste handling and methane destruction, industrial processes and gases. • **Background**: The Reserve is a non-profit organisation. It began as the California Climate Action Registry which was established by the State of California in 2001 to address climate change through voluntary calculation and public reporting of emissions. The Reserve still serves as an approved Offset Project Registry (OPR) for the State of California's Cap-and-Trade Program (a compliance market), in addition to establishing a national voluntary carbon credits program. The protocols are country specific and limited to North and Central America. For example, there are separate protocols for grasslands in the USA and Canada. Guatemala, Mexico, Panama and the Dominican Republic also have protocols for some project types.
GGR coverage	• The Reserve is developing a protocol for biochar in U.S. and Canada. It has established protocols for nature-based solutions such as soil management. Other GGR technologies covered in this study are not eligible for carbon credits under The Reserve.
Governance structure	• The Reserve is overseen by a Board of Directors, made up of representatives from state government, business, environmental organisations and academia. This is further divided into advisory and governing boards. • **Methodology development** – The Reserve allows new protocol suggestions to be submitted by stakeholders via a concept form. Staff conduct brief internal reviews of the submitted concept and supported documentation before meeting with the wider team. The potential of the protocol concept is assessed several factors including direct and indirect emission reductions, how difficult it is to establish a standardised approach to baselining and additionality, and the likelihood of project activities added to cap-and-trade schemes in the future. If the potential protocol is considered to have good potential, further internal research is conducted before a formal scoping meeting is held with interested parties. To initiate the protocol development process, the Reserve assembles a multi-stakeholder voluntary workgroup to review the draft protocol prepared by the Reserve. Following integration of feedback, the protocol is presented for public consultation. Comments from the public are addressed before the protocol goes to the Reserve's Board of Directors who must vote to adopt the protocol at a quarterly board meetings. Once the protocol has been adopted, the Reserve continues to solicit, document and respond to public feedback and comments. However, there does not appear to be requirements for periodic reviews. Further details can be found in the Reserve Offset Program Manual.
Information rights	The Climate Action Reserve and the Service Provider (APX Inc.) reserve all rights in the Program and the Software.
No of projects	As of 19th May 2023, 840 projects were listed/registered with the Reserve. As the protocol is under development, none are biochar projects. 36 of these projects were listed/registered in 2023.
Sustainability requirements	• In general, the Reserve requires project developers to demonstrate that the project "will not undermine progress on other environmental issues" such as air and water quality, endangered species and natural resource protection, and environmental justice. The project must not have negative impacts in these areas. When registering a project, the project developer must sign an Attestation of Regulatory Compliance form to confirm that the project is **in compliance with all applicable laws, including environmental regulations**, during the verification period. • Individual protocols may also contain requirements specifically designed to ensure environmental and social safeguards. For example, the draft biochar protocol limits the proportion of contaminants and mineral additives by dry weight in the feedstocks used for biochar production.
Key documents	• Reserve Offset Program Manual (March 2021) – LINK • Public registry – LINK • Workgroup Review Draft v1.0 of Biochar Protocol – LINK • Draft Biochar Feedstocks List – LINK • Draft Biochar End Uses List – LINK • Terms of Use – LINK

Overview: Climate Action Reserve (2/2)

Biochar

MRV specifics	
MRV and accounting basics	**Baselines** • Eligibility criteria are used to ensure that baseline estimation methods and emission factors prescribed by the protocol are relevant and appropriate to the geographical region of the project. **Additionality** • Projects are deemed eligible from an additionality perspective if they pass both of the following tests: 1. Legal requirement test. **If implementation is required by law, projects are likely to be non-additional**. A project passes this test when there are no laws, regulations etc. requiring its implementation. The protocols require project developers to review federal, state, local or other regulations and assess whether they require the implementation of the project. 2. Performance standard test. The Reserve protocols considers financial, economic, social and technological drivers that might make a project an attractive investment irrespective of carbon offset revenues. **Permanence** • The Reserve defines permanence as "being equivalent to the radiative forcing benefits of removing CO2 from the atmosphere for 100 years." In the case of biochar application, a permanence factor may be used to estimate what proportion of the biochar applied will meet this definition. • The Reserve maintains a buffer pool composed of credits from project types with identified risk of unavoidable reversal. The buffer pool contributions are established by each protocol, in accordance with the best available literature.
Verification and crediting	• **Verification –** Project methodologies do not need to be validated as the methodology is specified in the protocol as as part of the eligibility criteria. The Reserve requires periodic third-party verification of all GHG projects and their documentation, monitoring data and procedures used to estimate GHG reductions or removals. This is generally on an annual basis. Nine third-party verification bodies have been approved to date[1]. • All protocols require that GHG reductions are quantified based on actual project monitoring data as opposed to projections. The Reserve requires a monitoring plan for each project. At a minimum, this includes the frequency of data acquisition, record keeping plan, frequency of instrument field check and calibration activities, procedures to ensure the project passes the legal requirement test, and the role of individuals involved in monitoring. • **Crediting –** The CRTs represent one metric tonne of CO_2eq reduced or sequestered. They are issued based on the reduction or removal reported by the project and confirmed by an approved verification body. CRTs can also be transferred into Verra's Verified Carbon Units, VCUs, a global carbon credit program. However, VCUs cannot be turned into CRTs. The length of time projects can claim credits for is defined in each protocol. For all sequestration projects, the crediting period may be up to 100 years. The proposed crediting period for biochar is up to ten years. • The project must provide monitoring reports each reporting period for the length of the crediting period. The length of both periods depends on the protocol. For biochar, reports must be prepared at least once every 12 months for up to ten years. There are no provisions at present around transfer of liability to the government.
Treatment of uncertainty	• Uncertainty is treated in individual protocols. As mentioned previously, the Reserve maintains a buffer pool of credits sized by the risk of unavoidable reversal for each protocol. • The Reserve uses the eligibility criteria to rule out projects with more uncertain elements. For example, a list of allowed feedstocks is provided as part of the biochar protocol. Furthermore, protocols are only applicable to regions where the Reserve has all of the required datasets.

1. LINK

Climate Action Reserve's approach to certifying biochar

Biochar

Additional information: The Climate Action Reserve's U.S. and Canada biochar protocol is currently under development. The latest draft version from March 2023 was reviewed, but will likely differ from the final adopted version. The protocol clearly lays out minimum standards for monitoring, reporting and verification for most protocol aspects, including sampling of biochar. A chapter on monitoring parameters is yet to be released . This should fill any gaps in the protocol's monitoring stance, particularly for monitoring ongoing performance after application of the biochar.

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: Material inputs	• The Reserve has published a draft list of eligible feedstock. It allows biomass that is a waste stream, by-product or residue from forest, agricultural and other industries such as wood processing. Production emissions are not quantified for feedstocks that are waste or by-product materials. • It also allows biomass grown under certain conditions for the purpose of producing biochar (known as "purpose-grown" feedstocks). For these feedstocks, only fossil fuel consumed by equipment for cultivation and harvesting of feedstock in included. Emissions associated with fertiliser or pesticide use are currently not included for these feedstocks. [NEEDS IMPROVEMENT]
Feedstock production	Measurement: Quantifying counterfactual case and indirect land use change emissions	• The feedstock eligibility criteria exclude feedstocks that may lead to or result from land-use change or the conversion of a site to a vegetation site with a lower-carbon density. Counterfactual fates are assumed in the eligible biochar feedstocks draft list, but, to take a conservative approach, the baseline emissions associated with these counterfactual fates are assumed to be zero. [SATISFACTORY] • Under the performance standard test, waste and by-product biomass feedstocks are considered, by definition, to be typically not put to productive uses and have short lifespans before the carbon contained is released. Therefore, the removal is "additional" and deemed not to contribute to iLUC emissions. A separate test is used for "purpose-grown" feedstocks which may result in iLUC emissions; projects using these feedstocks must demonstrate that the feedstocks were acquired from marginal cropland locations or reclaimed mining sites, making ILUC emissions zero. [NEUTRAL]
Feedstock production	Methodology: Field emissions	• Emissions associated with fertiliser use are not included for "purpose-grown" feedstocks (e.g. crops). Other field emissions are not included in the draft protocol. [NEEDS IMPROVEMENT]
Production process	Methodology: Co-products	• The Reserve is considering using a proportional adjustment factor to account for situations where biochar is not the only product or some of the biochar produced is not being used for the project. [SATISFACTORY IF ENFORCED]
Other impacts	Methodology: Co-benefits	• Co-benefits are currently not included. This is because the scale and scope of these benefits are deemed too uncertain to be incorporated into a standardised quantification approach, particularly for practical monitoring and verification measures. Co-benefits will be considered for future updates and/or may be accounted for by other protocols that may address the benefits more effectively. For example, the soil enrichment protocol. [NEUTRAL]
Biochar decomposition	Measurement: Decomposition	• For most use cases, the permanence factors are calculated based on: the hydrogen to organic carbon ratio (determined from laboratory analysis for each biochar batch and dependent on the production process) and the mean annual soil temperature (data provided by the Reserve). It is considered to be 100% for addition to cement, gypsum, mineral plaster, clay and permanent storage structures. [SATISFACTORY IF ENFORCED] • The Reserve is yet to release its minimum standards for monitoring parameters. Once finalised, this will list the necessary monitoring parameters to calculate baseline and project emissions, their units, frequency and whether they can be calculated, measured, referenced or based on operating records. [SATISFACTORY IF ENFORCED]

Expanding standards to new GGR technologies – Climate Action Reserve

DACCS

Developing a new methodology for DACCS is **expected to be moderately challenging** because:

- The Reserve currently has no methodologies for CCS or direct air capture.
- However, precedence set by other standards and national regulations may aid with drafting new methodologies.

ERW

Developing a new methodology for enhanced rock weathering is **expected to be significantly challenging** because:

- Whilst soil enrichment is covered by the standard, other ERW processes aren't included in existing methodologies. For example, flows of weathering products and impact on ocean alkalinity.
- ERW still carries inherent uncertainties, which require continued experimentation and research to resolve.
- MRV protocols must rely on modelling to a degree, alongside additional field testing. To date, no ERW models have been fully validated.

BECCS

Developing a new methodology for BECCS is **expected to be moderately challenging** because:

- Biomass provisions can follow the biochar methodology and other nature-based carbon reduction methodologies.
- However, the Reserve currently has no methodologies for CCS or direct air capture.

Buildings

Developing a new carbon negative building materials methodology under is **expected to be moderately challenging** because:

- Original provisions need to be developed regarding obtaining CO_2 from eligible sources, accounting and measuring the exact amount of CO_2 stored in products, separation of carbon removals and emissions reductions (via reduced cement demand) and tracking end use of building materials.
- However, the Reserve has already developed a low-carbon cement methodology which accounts for energy used in the production process

Biochar

Already covered ✓

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging.**

- Due to the relatively limited scope of the Reserve, it has limited current applicability to ocean removals. It will likely be challenging to develop a new methodology, particularly with evaluation of baselines, tracking storage in DIC, and geological CO2 sequestration.
- However, the provision around maintaining a buffer pool (in case of non-permanence) as well as a general requirement to have all removals be over 100 years could potentially be transposed.
- The lack of strict validation requirement could suit ocean removals (due to limited opportunities for direct measurements), but an opportunity to recognise the importance and role of modelling should be emphasised.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: Climeworks & Carbfix (1/2)

DACCS

General description	
Description and classification	• Climeworks and Carbfix have produced complementary methodologies in 2022 that work together to verify DACCS projects. The methodologies themselves have been validated by the independent quality and assurance company DNV, in respect of the ISO 14064-2 standard. The Climeworks methodology encompasses the Direct Air Capture and CO_2 post-capture treatment steps prior to transportation whilst the Carbfix methodology covers the geological CO_2 storage aspect. Neither methodology covers the CO_2 transport component of a project. • **Classification**: Technology specific methodology for the assessment of GGR through DACCS. Geographical coverage is not limited, and therefore taken to be global. • **Background**: Climeworks is a solid sorbent DAC technology developer. Carbfix is an Icelandic company that has developed a novel approach to capturing and storing CO_2 through rapid mineralisation with subsurface igneous rocks. Climeworks and Carbfix aim to contribute to the standardization and scale-up of high-quality, permanent removals.
GGR coverage	The joint methodology is dedicated to carbon removal via DAC and underground mineralisation storage. Together the methodologies only cover a subset of DACCS configurations; namely solid-sorbent capture with a desorption temperature below 120°C and storage via rapid mineralisation or supercritical CO_2 injection. Excluded storage methodologies include sedimentary basins and enhanced oil recovery. The Carbfix methodology explicitly notes that it could also be used in conjunction with point source carbon capture on fossil-based CO_2 streams to generate emission reductions.
Governance structure	The methodologies are standalone documents developed by the technology developers intended to provide standards that can be third-party verified and communicated to customers. There is no overarching governance structure, standard, or registry to issue and sell credits in compliance or voluntary markets. **Methodology development** – Although the methodologies were released together, both allow for other external methodologies to cover the complementary aspects of the project value chain. Nevertheless, Carbfix notes that the Climeworks methodology is the only approved methodology that currently reaches its requirements. No public consultation was implemented in the initial methodology development but the companies welcome review and comment on the validated methodologies. DNV both validated the methodologies in respect of the ISO 14064-2 standard and verified the activities of Climeworks' Orca plant.
Information rights	No information is provided on the information rights associated with the methodologies
Number of projects / credits	The methodologies have only been applied to the Climeworks Orca site and Carbfix technologies. No credits are issued through the methodologies to registries or markets; however, the methodologies has been used to provide 3rd party validated GGRs sold bilaterally to Partners Group and Microsoft, Shopify and Stripe early this year from the Climeworks Orca site.
Sustainability requirements	Both methodologies requires projects do no net environmental or social harm and comply with applicable local environmental, ecological, and social statutory requirements. Furthermore, projects shall be installed according to national best practices and national statutory requirements. Access to water shall be according to local permits. Carbfix requires that all geological storage sites shall be approved by local authorities and hold relevant geological storage permit for CO_2 injection and subsequent wells shall be drilled according to national or international best practices and national statutory requirements.
Key documents	• Climeworks DAC Methodology – LINK • Carbfix Geological Storage Methodology – LINK • DAC+S methodology validated by DNV - developed and implemented by Climeworks and Carbfix as partners for permanent carbon removal • Partners Group signs carbon dioxide removal agreement • Climeworks delivers third-party verified CDR services

Overview: Climeworks & Carbfix (2/2)

DACCS

MRV specifics	
MRV and accounting basics	**Baselines** • For the Climeworks DAC methodology the baseline emissions without the project are zero as the project has no purpose other than the CO_2 removal. • The Carbfix methodology states that without the implementation of the project there would not be any geological CO_2 storage, therefore the baseline scenario shall only be assessed and described at the CO_2 capture project level. Focussing on DACCS, this results in an full chain project baseline of zero emissions as stated by the Climeworks methodology. **Additionality** • Climeworks uses the currently active UNFCCC CDM "Tool for the demonstration and assessment of additionality" based on economic or financing barrier analysis. • Carbfix requires projects to undergo additionality testing and additionality shall be demonstrated for the full process chain (CO2 capture, transport and storage). For demonstration of additionality, the stages of the project shall be assessed by both of the following requirements: 1. A statutory requirement test to ensure the project is not required by national or regional law or legislation, 2. An additionality test using the UNFCCC CDM TOOL01 for the demonstration and assessment of additionality. This could include tests such as FOAK, investment, barrier, and common practice analysis. **Permanence** • Solubility trapping with full CO_2 dissolution and CO_2 mineralisation to produce carbonate rocks is assumed to be a permanent storage with no ongoing reversal risk if reservoir pressures are sufficient to maintain the CO_2; however monitoring procedures are required nonetheless. • No buffer pool or other permanence mechanism is included in the methodologies. • Post closure monitoring and transfer of liability to the relevant authorities must follow requirement defined by local legislation, if available. If not, monitoring must continue at reduced frequency for at least 10 years, unless at least 95% mineralization can be demonstrated, until data indicates no evidence of continued CO_2 release and trends towards long-term stability.
Verification and crediting	**Verification** – Neither methodology refers to any specific verification or validation process requirements. When assessing the Climeworks Orca plant, DNV conducted an onsite audit, where a review of documentation, interviews, and site inspection verified that Climeworks and Carbfix are operating in accordance with the methodologies. **Crediting** – CO_2 is measured at the injection wellhead of the storage site before project emissions are subtracted from the stored CO_2 quantities to calculate the total GGR for crediting. The methodologies do not fundamentally connect to a wider standard that issue credits. If a party would require credits from both methodologies (and a CO_2 transport methodology) to claim negative emissions is unclear.
Treatment of uncertainty	Both methodologies require that all measurement devices shall be calibrated according to manufacturer recommendations or industry best practices, and allow measurements with uncertainty of 5% or better. Carbfix states all emission sources that are less than 0.5% of operational emissions individually can be assumed negligible and therefore insignificant if the sum of all such sources is less than 5% of total operational emissions.

Climeworks and Carbfix's approach to certifying DACCS

DACCS

Process	Uncertainty Type	Approach of the methodology
CO_2 capture	Methodology: Energy Input	• The Climeworks methodology requires project level assessment of the data source on the emissions intensity of electricity and heat suppliers. In general, data is expected to be taken from national or international standards, supported by literature, or supported by extensive data. [NEUTRAL] • The methodology does not explicitly require the temporal correlation of electricity consumption and generation. No assessment of the impacts of energy demand for direct air capture on the wider energy system or other environmental aspects, such as land use change, is included. [NEEDS IMPROVEMENT] • The methodology does not specifically address the potential to utilise waste heat however does include the flexibility to give and justify an emissions factor for heat supply. [NEUTRAL]
CO_2 transport and storage	Methodology: Energy Input	• Carbfix requires that emission factors shall be derived from the latest values published by the IPCC, except for electricity/thermal usage which shall be derived from nationally determined emission factors and/or information provided by the energy supplier. [SATISFACTORY] • Neither methodology covers the CO_2 transport section of the value chain directly, although Carbfix does provide some general guidance on the content and scope of suitable methodologies and a placeholder for future indication of applicable methodologies. [NEEDS IMPROVEMENT]
Geological storage	Measurement: CO_2 migration, trapping and leakage	• The supporting Appendices suggests that geologically stored CO_2 should store for a minimum of 1000 years with a leakage rate of less than 0.1% per year, however this is not explicitly defined within the core methodology. [NEUTRAL] • Carbfix requires both in situ sampling and quite rigorous modelling from initial site characterisation all the way to post-closure. The methodology requires geostatic, flow, and geochemical models or full reactive transport schemes. The project proponent shall create/update reservoir model(s) to evaluate conformance and predict future performance of the geological storage reservoir. [SATISFACTORY] • Monitoring requirements include tracer tests reported within 5 years of first injection and then at intervals less than the renewal period, annual sampling of selected monitoring wells, CO_2 gas detectors and monthly inspections for the injection well, surface flux measurements every two years, and annual sampling of natural spring chemistry. The project shall execute activities in the subsurface monitoring program for the duration of injection and the post-injection period until closure. [SATISFACTORY] • To validate modelling prediction sampling requirements include natural isotope / reactive tracer analysis, mass balance calculations, or drill core sampling to inform the behaviour of injected CO_2. If major deviations are reported between the expected and observed performance of the geological storage reservoir the project must adjust injection rates or the subsurface monitoring plan. [SATISFACTORY] • To ensure long term monitoring and liability management, a closure plan must describe the closure activities, the monitoring requirements for the post closure period, and performance indicators and conditions to be met before liability transfer to the relevant authorities can be achieved. Storage site closure, post closure monitoring, and transfer of liability to the relevant authorities must follow requirement defined by local legislation, if available. If not, monitoring must continue at reduced frequency for at least 10 years, unless at least 95% mineralization can be demonstrated, until data indicates no evidence of release and trends towards long-term stability. [NEUTRAL] • The methodology only recognises solubility trapping, mineralisation, and supercritical CO_2 injection. [NEUTRAL]

Expanding standards to new GGR technologies – Climeworks and Carbfix

DACCS

Expanding the scope of the existing DACCS methodology to include other CO_2 capture technologies and CO_2 storage methods would only **be moderately challenging**:

- For Carbfix's storage methodology only the monitoring section would require updating to account for different leakage pathways.
- The Climeworks methodology should be easily modifiable for other capture technologies with minor adjustments to account for different chemical consumption patterns and increased energy demand.

ERW

Climeworks and Carbfix are **highly unlikely** to consider expanding their methodology to ERW as this fall outside the scope of their own technology solutions.

BECCS

Carbfix's methodology explicitly states it could be used for the storage of biogenic CO_2 captured from point sources. The CO_2 storage methodology could therefore **easily be used for the geological CO_2 storage component of BECCS projects**.

Buildings

Climeworks suggests it is **highly unlikely** to accept storage solutions that are not geological in nature collaborating with the CO_2 capture methodology. Carbfix are **highly unlikely** to consider expanding their methodology to storage in buildings as this fall outside the scope of their technology.

Biochar

Climeworks and Carbfix are **highly unlikely** to consider expanding their methodology to biochar as this fall outside the scope of their own technology solutions.

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging.**

- Carbfix's methodology does not explicitly mention CO_2 captured from the ocean as supposed to the atmosphere. However, Carbfix's willingness to accept a variety of other CO_2 sources suggest they could **expand the scope**. The CO_2 storage methodology could therefore likely be adopted for Direct Ocean Removal techniques that require geological CO_2 storage.
- However, the methodologies do not cover most of the CO_2 flows in other ocean removal projects, e.g., air-sea gas exchange or DIC storage. Therefore, the Climeworks / Carbfix methodology is unlikely to be a source on which to base ocean removal standards.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Overview: Carbon Standards International EBC C-Sink Certification (1/2)

Biochar ERW

General description	
Description and classification	• Carbon Standards International (CSI) certifies C-sink credits for biochar-based carbon sinks and carbon sinks created by enhanced rock weathering in agricultural land. CSI also oversees the European Biochar Certificate (EBC) which certifies the sustainable production of biochar but is separate to the C-sink standard and does not include carbon removal. The biochar C-sink methodology is sometimes still referred to as an EBC C-sink standard as a result. • **Classification**: CSI has two tech-specific standards for certifying carbon sinks. • **Background**: The currently published CSI methodologies were created by Ithaka Institute and delivered by CSI. The biochar methodology was developed in 2020 and updated to version 2.1 in February 2021. Documents published by CSI state that the biochar methodology is applicable to Europe, USA and Canada. Beyond these countries, specifically tailored EBC packages can be created for certification. The ERW methodology, version 0.9, was released in October 2022. For ERW projects outside of the EU, currently published documents state that projects must send an application to Carbon Standards International to add country-specific legislation information and agroclimatic data. However, it is our understanding that CSI intends for C-sink to be a global standard.
GGR coverage	The C-sink certification covers biochar-based carbon sinks, as well as carbon sinks created by enhanced rock weathering in agricultural land.
Governance structure	• The standard is operated by Carbon Standards International (CSI) which is part of the Easy-Cert group, based in Switzerland. Easy-Cert owns 85% of CSI as of 2023[1]. CSI is overseen by a general assembly, board of directors and management board. There is an impartiality committee which interacts with the board of directors[2]. • **Methodology development** – Ithaka Institute developed both technology methodologies. Ithaka Institute is an international non-profit research foundation headquartered in Europe. Updates must be completed at least every three years. For regular updates, a first draft is prepared by Ithaka and, if necessary, agreed with the Scientific Advisory Committee. It is then assessed by a Technical Committee at CSI and, depending on the technology, then reviewed by an external expert group. An agreed pre-final version then progresses to a public consultation. Comments from the consultation are assessed by the CSI Technical Committee and forwarded to scientific management with comments. Feedback from the consultation is responded to and the final version published. Further details can be found in the Methodology development link below.
Information rights	The right to use the “Carbon Sink Registered” seal is acquired by registration of the corresponding C-sink by an EBC-accredited C-sink trader. There are costs associated with the registration of the C-sink and C-sink dealers.
Number of projects / credits	As of 17/05/2023, there are 2920 C-sink potential projects registered, 789 of these in 2023 alone. However, only 290 C-sink projects have been issued with C-sink credits, 59 of these in 2023. However, it is our understanding that the registry may not include all
Sustainability requirements	• Generally, the production **must meet all local and national regulations** on environmental protection and health and work safety. • For ERW, the rock powder must meet all relevant national and European regulations on fertilisation and soil protection. This includes analysis of the rock for nutrients and certain trace elements. A list of analytical methods is under development. Conservative maximum application rates are also stipulated to avoid overloading the soil. • The ERW standard only allows applications in certain conditions (low wind, not dry) to avoid particle drift and dust development. Further guidelines are under development.
Key documents	• C-sink biochar methodology – LINK • C-sink ERW methodology – LINK • C-sink registry – LINK • Templates for new methodologies – LINK • Methodology development – LINK • Biochar additionality test – LINK

1. LINK 2. LINK 3. LINK

Overview: Carbon Standards International EBC C-Sink Certification (2/2)

Biochar ERW

MRV specifics	
MRV and accounting basics	**Baselines** • Physical measurements of soil properties before application are required to inform modelling of C-sink potential. **Additionality** • The standard recently published details of its additionality tests for biochar C-sink certification. It includes assessment of regulatory requirements and contribution to the price of biochar and/or biomass. In the event the latter cannot be proven, the standard states that the UNFCCC CDM "Tool for the demonstration and assessment of additionality" may be used in place. It is unclear if these tests will be applied retroactively to credits that have already been issued. For ERW, there are limits to the total annual quantity of powdered rock that may be applied to a land area, but this is largely due to environmental concerns. The final location and owner of the site where the C-sink is created should be registered to avoid duplicate certificates. **Permanence** • Permanence requirements are technology specific For example, the ERW standard states that the land cannot be classified as potential construction ground by local authorities. This is to avoid the powdered rock being displaced. • There are currently no provisions around transfer of liability to the government.
Verification and crediting	• **Verification –** For the production of the biochar or rock powder, the certification is carried out by q.inspecta GmbH, an accredited certification body which is also part of the Easy-Cert group. This involves on-site visits, sampling of rock powder and checks on environmental protection and work safety. • For monitoring after production, the standard requires an EBC accredited tracking system to be used for biochar C-sinks. The standard sets out principles for such a system but does not have its own methodology. The ERW methodology is under development and details of verification for ERW C-sinks are yet to be released . • **Crediting** – The process for biochar has two-steps. 1) The EBC certifies the C-sink (carbon sink) potential up to the factory gate of the biochar producer. This includes carbon expenditures in feedstock transport, storing and production. 2) From the factory gate, the C-sink trader has to ensure tracking of the product to the final sink application and assess associated emissions. This tracking system must be accredited by the EBC and may be developed and implemented by C-sink traders and trading platforms. After application, the C-sink potential can be converted into tradable C-sink certificates by entering the ultimate C-sink value into the EBC's C-sink public registry. However, EBC does not have a full methodology for emissions after application and has so far only approved one C-sink trader, carbonfuture[3]. • For ERW, the methodology and crediting system is under development. The current version of the methodology allows credits can be claimed for each application. However, there are limits to the quantity and frequency of application.
Treatment of uncertainty	• The standard tackles uncertainty by applying conservative safety factors to the C-sink potential or by excluding certain use cases entirely. These uncertainties are determined by each technology and are not uniform across the standard. For example, ERW cannot be applied to non-agricultural land.

Carbon Standards International's approach to certifying biochar

Biochar

Additional information: There are two biochar methodologies; EBC Carbon Sink Certification (for industrial biochar production) and Global Artisan C-Sink (for manual biochar production). The former was analysed in this review as industrial biochar production was deemed more likely in the UK.

Process	Uncertainty Type	Approach of the methodology
Feedstock production	Methodology: Material inputs	• The standard only allows for "carbon neutral feedstocks". Eligible feedstocks must either be the residue of a biomass process operation or feedstocks where the biomass removal did not, over the reference period, lead to the reduction of the total carbon stock of the system in which the biomass was grown. A positive list of eligible feedstocks is provided which includes primary (e.g. crops) and secondary (residues/waste) feedstocks[1]. [SATISFACTORY] • Pesticide and fuel inputs for agricultural and harvesting processes are included in the flat margin of safety factor applied to total project emissions and subtracted from the removals potential. [SATISFACTORY] • Emissions from fertiliser use are included if the biomass was deliberately grown to produce biochar, i.e. was the single or main product of the field. Considering the standard's approach to co-products (see below), this is interpreted as deliberately grown to be used in the process that produces biochar, i.e. biochar does not need to be the dominant product from the pyrolysis process for fertiliser emissions to be included. [SATISFACTORY IF ENFORCED]
Feedstock production	Measurement: Quantifying counterfactual case and indirect land use change emissions	• The standard only allows feedstocks meeting the criteria described above. If feedstock cultivation leads to a reduction in the total carbon stock of the system in which the biomass was grown, this feedstock will not be eligible under the standard. This accounts for direct land use change. However, indirect land use change emissions are not accounted for. [NEEDS IMPROVEMENT]
Feedstock production	Methodology: Field emissions	• As stated above, emissions from fertiliser use (including N_2O emissions) are included. Measurements of other field emissions from biomass production are not required. [SATISFACTORY] • Methane and nitrous oxide emissions which may result from suboptimal biomass storage are included. Best practice guidelines are set out and, if these measures cannot be met, safety factors are provided to deal with the uncertainty. [SATISFACTORY]
Production process	Methodology: Co-products	• Co-products, such as bio-oil or syngas, are not accounted for. All emissions associated with feedstock cultivation, processing, transport and pyrolysis are allocated to the biochar. [NEUTRAL] • If the net energy balance of biochar production facility is positive, the positive energy balance may be credited as emissions reduction with another scheme, but not with the EBC. It cannot be used to increase C-sink potential or offset emissions elsewhere in the supply chain. [NEUTRAL]
Other impacts	Methodology: Co-benefits	• Co-benefits of biochar are not accounted for. [NEUTRAL]
Biochar decomposition	Measurement: Decomposition	• For modelling biochar applied to soil, the annual rate of degradation must be applied according to the organic H/C ratio of the biochar and must be at least 0.3%. Soil temperature is not accounted for in the calculation, although the minimum 0.3% rate is conservative. [NEEDS IMPROVEMENT] • For integration in construction or industrial materials, it is considered permanent until disposed of. [SATISFACTORY] • A second tracking system, developed by a C-sink trader and accredited by EBC, must be used to calculate emissions from the factory gate to the incorporation of biochar in soil or materials. To date, EBC has only approved one C-sink trader, Carbonfuture. [SATISFACTORY]

1. LINK

Carbon Standard International's approach to certifying ERW

ERW

Additional information: The ERW approach is under development and models and methodologies are yet to be validated. Unlike other technologies such as DACCS, GGR via ERW is a continuous process where the amount of CO2 sequestered increases over the project lifetime. Quantifying the CO2 sequestered over time by ERW is an ongoing area of research. The standard proposes that ERW C-sink credits are recognised as contributing to the mitigation of anthropogenic emissions but are not to be used in CO2 compensation markets. In addition to the model and methodology being under development, this is because the temporal aspect of removals is key in offsetting.

Process	Uncertainty Type	Approach of the methodology

Weathering	Measurement: Proportion of bicarbonate ions from weathering process contributing to ocean alkalinity and those to carbonate precipitation	• The standard suggests a method for determining how much carbon has been removed. However, it is yet to be validated. Some measurements for baselining are suggested but full requirements for these methods are yet to be released. Key released details of the approach are detailed below. [NEEDS IMPROVEMENT]
		  ◦ The model is based on a silicon normalised weathering model as silicon is present in all of the rock types eligible under the standard.
		  ◦ The overall weathering rate is determined by physical measurements of soil pH, and data that can be obtained for the nearest reference location for agroclimatic data (soil temperature, moisture throughout the year), with some default values used for soil CO_2 concentration and biogenic weathering agents for now. Further appendices on measurement methods allowed are under development.
		  ◦ Secondary clay minerals are accounted for with a safety margin of 10% being deducted from the CDR potential.
		  ◦ The standard assumes 20% of the bicarbonate ions result in carbonate precipitation, resulting in less CO_2 sequestration than the bicarbonate ions reaching the ocean.

Additional sources of leakage	Method: Leakage via outgassing from effluent	• A safety factor of 14% is deducted to account for outgassing from the effluent. This value is calculated from academic literature. [SATISFACTORY IF ENFORCED]
Full chain	Method: Counterfactual	• The standard requires soil analysis pre-application of crushed rock to establish the baseline. However, requirements for this analysis and further monitoring are yet to be developed and released. [NEEDS IMPROVEMENT]
Other impacts	Method: Co-benefits	• Co-benefits are not accounted for. [NEUTRAL]

Overview: Planetary (1/2)

OAE

General description	
Description and classification	• Planetary's current mineral OAE standard governs the addition of fine magnesium hydroxide particles – $Mg(OH)_2$ – in slurry form to wastewater or other industrial outfalls that discharge into the ocean. • **Classification**: The standard is technology specific to mineral OAE, and is not applicable to other ocean removals (electrochemical OAE or DOR), nor terrestrial GGRs. • **Background**: The standard has been collaboratively developed and agreed with Shopify (expected to be the first purchaser of credits) and is on Version 2.0 following laboratory experimentation and learnings from a methods test (conducted in Cornwall, UK in Sep 2022) and based on the scope of Planetary's emissions accounting protocol. Longer-term field trials are planned in 2023.
GGR coverage	• Planetary is an ocean-based GGR company funded in part through the Musk Foundation through X-Prize. The company developed its mineral OAE standard to govern its own OAE projects based primarily in Canada and the UK. The standard, currently in Version 2.0, has been made "open source" in order to provide a consistent framework that other mineral OAE projects can use to develop the industry overall. The protocol scope is not geographically restricted, and is intended to help develop mineral OAE projects using a consistent framework for purchasing mineral OAE GGR credits. Planetary's early work in the UK, leading to the Cornwall site selection and the Plymouth Marine Laboratory collaboration, was funded in 2021 by the BEIS GGR competition (Phase 1).
Governance structure	• The company is a privately held and backed by venture capitals, accelerator/incubators, and angel investors. It was previously known as Planetary Hydrogen before changing name to Planetary Technologies. • **Methodology development** – the GGR standard and its subsequent versions are being developed to support and provide transparency to initial Planetary OAE projects. Planetary is currently inviting participation in refining the MRV concepts and protocols, and is hosting discussions and debate through an online forum.
Information rights	• The standard is open source, with all information expected to be distributed and shared with the scientific community, GGR project developers and national governments.
Number of projects / credits	• There are currently no projects which are receiving credits through the Planetary MRV standard. However, the company is developing an initial project in Cornwall, partnering with Plymouth Marine Laboratory and the National Oceanography Centre. With presence and team members in Canada, the US, and the UK, Planetary is planning to launch additional trials in Canada in 2023 and a wider set of sites globally in 2024.
Sustainability requirements	• Other than emissions associated with LCA, the standard does not contain any additional sustainability requirements (for mineral sustainability, the standard merely states the benefits of magnesium hydroxide). While the standard does state that ".... the Planetary team is dedicated to ensuring, to the greatest extent possible given current knowledge, that ecological risks are minimized", there is currently no quantifiable requirement for assessment of these risks on regular monitoring intervals. Planetary has claimed it is targeting to revise and strengthen the sustainability requirements in the next iteration of the methodology.
Key documents	• Planetary MRV standard – LINK • Planetary Cornwall project overview – LINK • Planetary company overview – LINK • Planetary website – LINK • Planetary online forum site – LINK • Planetary online forum addressing feedback – LINK

Overview: Planetary (2/2)

OAE

MRV specifics	
MRV and accounting basics	• The GGR potential for credit generation is defined by the following equation: **CDR_{net} = CDR_{gross} x (CDR_{eff} – $CDRh_{back}$) – LCA_{emiss}** • **CDR_{gross}** = mass of mineral added x stoichiometric ratio between CO_2 consumed and mass of mineral added; **CDR_{eff}** = fraction of the theoretical CDRgross that is achieved within a 1 year period following the addition of alkalinity for a specific location, and is derived from laboratory/field and field experimentation and physical ocean modelling; **CDR_{hback}** = (see "Treatment of uncertainty" below); **LCA_{emiss}** = tonnes of CO_2 emitted in the production, transportation, and distribution of the total mineral mass used in the operation **Baselines** • The baseline emissions for projects is not assumed, and is expected to be determined from the above equation. • Some baseline information is required in order to determine the CDR_{hback}, such as the partial pressure of the CO_2 (pCO_2) in the waste water effluent* • The baseline CDR ratio (used to calculate CDR_{gross}) is assumed to be 1.25 tCO_2 removed for every tonne of mineral (magnesium hydroxide) added **Additionality** • Additionality considerations are given to the choice of magnesium hydroxide as Planetary's preferred mineral (low toxicity, slow dissolution kinetics, etc), and a stated goal to monitor ecological parameters (both negative and positive responses to alkalinity enhancements) and control alkalinity dosing rates, which may help reduce local impacts of ocean acidification. • A number of different monitoring techniques are listed, however none are explicitly stated as a requirement. Planetary believe it would be unrealistic to state hard requirements at this stage. **Permanence** • The standard assumes that any additional CO_2 drawn down via mineral OAE will behave in a similar manner to the mean residence time of alkaline dissolved carbon in the ocean. This is assumed to be app. 100,000 years, based on the annual input of alkaline carbon from rivers (0.3 GtC/yr), the alkaline pool of dissolved alkaline carbon resident in the ocean (about 34,000 GtC), and assuming steady state (Middelburg et al. 2020 – Link). While the standard does recognise that around half of the alkaline carbon within this timescale is eventually returned to the atmosphere, the timelines given are likely assumed to be "permanent" based on the timeline and expectations of other GGRs
Verification and crediting	Reporting and verification is required to be performed by an **independent third party**. This must include several key factors, a non-exhaustive list being: • The LCA emissions of the mineral used in the process must be properly audited - either directly by the 3rd party or through reliance on an external verifier. Planetary adapts the United States Environmental Protection Agency (EPA, 2022) scope language in order to maintain a system boundary and accounting scheme specific to each project site. • Records of periodic assays for the mineral product used. This may include particle size distribution (PSD), heavy metal content, and % mineral. • The alkalinity dosing records must be reviewed and matched to delivery load amounts. • The model must be validated with ocean sensing and its output aligned with the understanding of the OAE efficiency factor (CDR_{eff}). • The calculation of the CO_2 captured and sequestered must be assessed by the verifier on a regular time interval. • Metering must be shown to be accurate and reliable, and records must be maintained for at least ten years. **Crediting** –Planetary's credit generation potential is not explicitly explained in the MRV standard. However, it will likely be associated with the CDR_{net} value defined in the equation above.
Treatment of uncertainty	• The Planetary standard recognises that mineral OAE projects still hold some degree of uncertainty associated with data generation, verification, and estimation. Therefore, a holdback factor (CDR_{hback}) is introduced for every individual project which reduces CDR_{eff} in an "estimate and refine" approach*. • An initial CDR_{hback} of 0.15 is given for every project, which is expected to be the upper limit of uncertainty. However, holdback factors may be adjusted as follows: a "preliminary" 0.15 factor is given to each project, assuming that 1) a 2D model is completed, 2) effluent pCO_2 baseline is completed, and 3) mineral particle size distribution is determined. An "operational" factor of 0.10 is awarded upon completion of a 3D model**. Finally, a "mature" holdback factor of 0.02 is awarded upon model validation of at least 10 sensing events.

*This is understood to be a placeholder, with a more detailed methodology to be developed in the next iteration

**This model must incorporate site-specific mixed layer dynamics, relative buoyancy of effluent and vertical mixing rates, average wind speed, seasonal mixed layer depth changes, and sea surface roughness. The model must be validated based on at least 3 sensing events (1-week deployments of ocean sensors) - pH, temperature, salinity, pH, pCO_2 change against pre-alkalinity addition baseline.

Planetary's approach to certifying mineral OAE projects

OAE

Additional information: The Planetary MRV protocol acts primarily as a project MRV plan intended to give Planetary projects more legitimacy and transparency to produce and sell credits to a purchaser (i.e., Shopify). As such, while several factors (such as monitoring requirements, choice in alkaline mineral, etc) from Planetary's methodology will be more widely applicable to other mineral OAE projects, the standard was not intended to be used as a requirement for all projects.

Process	Uncertainty Type	Approach of the methodology
Air-sea gas exchange	Measurement: Retention of pCO2 depleted water in the ocean mixed layer until pCO2 equilibration can occur through air-sea gas exchange	• In Planetary's standard, air-sea gas exchange is most applicable to the CDR_{eff} variable (i.e,. the fraction of CDR_{gross} that is actually realised in the ocean within one year of the addition of alkalinity for a specific location). • Planetary explains that the present approach relies on numerical modelling to assess the efficiency of OAE in either increasing CO_2 drawdown or decreasing CO_2 outgassing. This reflects the current challenges associated with direct measurement of an increase in seawater DIC over the entire volume of seawater affected, primarily due to i) the time and space scales involved, ii) the continuous and significant dilution of the added alkalinity and affected seawater, iii) the natural background variability of seawater chemistry, and iv) the limitations of measurement precision and accuracy. [SATISFACTORY] • CDR_{eff} is calculated via [$CDR_{eff} = CDR_{model} / CDR_{gross}$] over a one year timespan. CDR_{model} refers to the 2D/3D model required to achieve a minimum preliminary or operations holdback factor (see "Treatment of uncertainty" in previous slide) which requires an effluent pCO_2 baseline and three sensing events including pCO_2 change against the baseline. Further "core measurements" which may indicate air-sea gas exchange changes include pH and total suspended solids/total alkalinity/DIC via discrete bottle samples. While this combination of in situ sampling and modelling is useful, the standard does not explicitly outline a comprehensive and continuous sampling/monitoring regime [NEUTRAL] • The CDR ratio is required to be updated via point of discharge conductivity, temperature and depth (CTD) sensor and pH measurements applied to the model every 3 months, and the CDR_{eff} is required to be updated every year. [SATISFACTORY]
Mineral dispersal	Measurement: Tracking mineral dissolution in the surface mixed layer	• Planetary consider mineral dispersion when calculating CDR_{eff} as a derivation from numerical simulations of effluent dispersion and regional oceanographic conditions. Models are re-validated with ocean sensing and DIC/TA spot measurements annually. [NEUTRAL]

Planetary's approach to certifying mineral OAE projects

Additional information: The Planetary MRV protocol acts primarily as a project MRV plan intended to give Planetary projects more legitimacy and transparency to produce and sell credits to a purchaser (i.e., Shopify). As such, while several factors (such as monitoring requirements, choice in alkaline mineral, etc) from Planetary's methodology will be more widely applicable to other mineral OAE projects, the standard was not intended to be used as a requirement for all projects.

<table>
<tr><th>Process</th><th>Uncertainty Type</th><th>Approach of the methodology</th></tr>
<tr><td>Secondary precipitation*</td><td>Measurement: Formation of secondary precipitates such as $CaCO_3$</td><td rowspan="2">• Planetary combines both secondary precipitation considerations with biotic calcification under "biotic and abiotic precipitation of $CaCO_3$". While the standard does recognise both of their potential to return trapped DIC CO_2 to atmospheric CO_2, they do not have a specific quantification or measurement mechanism in order to account for these [NEEDS IMPROVEMENT].
• Planetary assumes a CO_2 leakage of 0.0009%/yr, which they claim is consistent with annual $CaCO_3$ precipitation/burials in the global ocean. While this may be consistent with some scientific estimates, the standard does not have a comprehensive and analytically-backed leakage quantification requirement [NEEDS IMPROVEMENT].
• While Planetary recognises secondary $CaCO_3$ precipitation as a potential risk to OAE effectiveness, the company states that based on previous reported experimental results (Hartmann et al. 2022; Moras et al. 2022), as well as their own in-house experiments, it is possible to add alkalinity to seawater in quantities that stay below the precipitation threshold. However, there is a noticeable lack of explicit required verification for this assumption within the standard [NEEDS IMPROVEMENT].
• Planetary states that these types of bottle or beaker experiments do not account for the rapid dilution of alkalinity once added to wastewater and especially once entering the ocean (dilution has been shown to drop the concentration of alkalinity in seawater below precipitation thresholds at a rate far faster than the rate at which $CaCO_3$ precipitation can proceed – He and Tyka 2023). Planetary believes that its choice of magnesium hydroxide dissolves (and thus releases alkalinity) slowly and provides an additional layer of safety with respect to staying below marine chemical (and biological) thresholds. However, there is a noticeable lack of explicit required verification for this assumption within the standard [NEEDS IMPROVEMENT].</td></tr>
<tr><td>Biotic calcification response*</td><td>Measurement: Quantification of biotic calcification</td></tr>
</table>

*It is understood that Planetary is completing a comprehensive uncertainty analysis, addressing these and other factors, which is expected to be summarised in the V3 methodology update.

Overview: The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (1/2)

General description	
Description and classification	• The UK permits CO_2 storage activities under The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010. • **Classification**: General standard for carbon reduction and removals; general standard for carbon removals only; stand-alone methodology for one GGR technology; collection of best practices for standards; buyer's guidelines for GGR purchasing; other – please specify • **Background**: These regulations were developed as a partial transposition of the EU CCS Directive (in addition to amendments to the Energy Act 2008), which seeks to give a clear and consistent framework for assessing applications and permitting CO_2 storage activities across European countries.
GGR coverage	• The UK storage regulations (directed by the Energy Act 2008) cover any activities directly injecting and storing CO_2 into the subsurface of UK territorial waters (i.e., offshore within the UK exclusive economic zone). For GGRs, this would include CO_2 injection activities associated with DACCS, BECCS, and DOC (geological CO_2 storage component not DIC storage component).
Governance structure	• The UK storage regulations are primarily permitted through the North Sea Transition Authority (NSTA), with certain devolution granted to the Crown Estate and Crown Estate Scotland/Scottish Ministers for storage within territorial waters adjacent to Scotland. • Applications to the NSTA for CO_2 storage permits under the storage regulations occur in offshore licensing rounds, in which an application window is opened and applicants submit an application package for a license (granting temporary ownership of an offshore plot and potentially covering an initial appraisal term) after which which they may make an application for a storage permit (by submitting necessary information for a permit). • **Methodology development** – brief description of process for developing new methodologies. Is the process transparent? Is there an independent scientific advisory board? Is there a public consultation process? Is there a way to submit variation orders to existing methodologies for minor changes? Are there provisions for periodic methodology reviews?
Information rights	• Information rights are held by government, and successful storage licenses and permits are published on the NSTA website (public registry).
Number of projects / credits	• To date, there are 6 active licenses in the registrar, and in the most recent storage license round, 20 additional carbon storage licenses were provisionally awarded to 12 companies.
Sustainability requirements	• CO_2 storage applicants are required to include in their initial impact assessment proof that "there is no significant risk of leakage or of harm to the environment or human health".
Key documents	• The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 – LINK • UK CO_2 storage licenses – LINK • Recent UK CO_2 storage licensing round – LINK • EU CCS Directive – LINK

Overview: The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2/2)

MRV specifics	
MRV and accounting basics	**Baselines** • A baseline assessment may be initially determined through an appraisal period, in which the licensee measures key reservoir characteristics to include in a storage permit, and how they would potentially be affected by CO_2 storage activities. This contributes to a "baseline assessment" from which modelling make predict future injected CO_2 behaviour. Should real-time CO_2 behaviour be assessed to be deviating from the model (supported by the baseline assessment), then a corrective action plan may be implemented. • An application for a storage permit may be submitted by a holder of a license. Contents of an application include information on the CO_2 (quantity, date, composition, injection rates, location, etc), a proposed monitoring plan in line with Annex II of the CCS Directive, a corrective measures plan, and the provision post-closure plan. • If successful, a storage permit will be awarded which include (non-exhaustive) the location of the storage site and the storage complex, any relevant information concerning the hydraulic unit, the operational requirements for storage (total quantity of CO_2 authorised, reservoir pressure limits, maximum injection rates/pressure, etc), provisions* relating to injection of CO_2, provisions relating to monitoring and reporting (including the monitoring plan and notification of leakages/significant irregularities) and a corrective measures plan. **Additionality** • Applicants must also demonstrate financial security against the proposed storage activities, which is intended to reduce the possibility of state liability assumption within the private-held operator monitoring period in case of financial burden or hardship. **Permanence** • In line with the CCS Directive, permanence is assumed through continuous monitoring and verification (see above and below). Post-closure, the private operator is expected to hold liability for monitoring the storage site for at least 20 years, after which it might transfer long-term liability to the state with a financial contribution covering another 30 years of monitoring.
Verification and crediting	• **Crediting** – These regulations do not produce credits. However, projects with a CO_2 storage permit may be licensed independently through the UK ETS authorities as eligible to claim emissions reductions (relevant for compliance markets) for their own or third parties or may provide independent credits through an independent or voluntary accreditation scheme, although it is expected that these would not be endorsed by the UK Government. • Monitoring must be based on a monitoring plan, which is updated every five years in accordance with Annex II of the CCS Directive. This takes into account changes to the assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge and improvements in best available technology.
Treatment of uncertainty	• There is limited discussion of uncertainty within the UK storage regulations themselves. In the CCS Directive, a discussion of uncertainty is contained to the models associated with predicting CO2 behaviour: "The uncertainty associated with each of the parameters used to build the model shall be assessed by developing a range of scenarios for each parameter and calculating the appropriate confidence limits. Any uncertainty associated with the model itself shall also be assessed." • While this does recognise that there is a certain degree of uncertainty associated with model development, and that this should be quantified and continuously improved, there is no explicit uncertainty limit required by the Directive.

*Provisions are specifically outlined in Schedule II of The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010

UK regulations approach to certifying CO2 storage

Process	Uncertainty Type	Approach of the methodology
Geological Storage	Measurement: CO_2 migration, trapping and leakage	• The standard requires that any leakage detected to be immediately reported to the necessary authority (possible resulting in credit or ETS free allocation surrender), and that leakages are immediately corrected via the pre-approved corrective measures plan initially outlined in the application and agreed with Government. [SATISFACTORY] • The regulations require a consistent monitoring regime (beginning with a comprehensive baseline assessment) coupled with comparisons of CO_2 in situ behaviour to predicted 3D modelled behaviour, and require any significant irregularities/deviations to be investigated and possibly corrected in accordance with the correction plan. [SATISFACTORY] • The monitoring plan must be updated in accordance with Annex II to the Directive, and in any event within five years of the approval of the original plan. [SATISFACTORY] • Long-term liability management is defined through the provisions in the EU CCS Directive, which requires a minimum of 20 years of post-closure monitoring by the private operator, after which liability may be transferred to the state with a financial contribution covering an additional 30 years of monitoring [SATISFACTORY] • The standard does not distinguish between different trapping mechanism, only that the CO_2 is "permanently contained" [NEUTRAL]

Overview: The EU Carbon Removal Certification Framework (1/2)

General description	
Description and classification	• **The EU Carbon Removal Certification Framework (CRCF)** is an overarching set of principles and rules that is currently being developed by the European Commission to certify GGRs activities across the EU. CRCF is not a certification scheme, but sets the rules and methodologies that future **certification schemes must follow under the EU Regulation**. • **Classification**: EU CRCF is intended to be a general standard for carbon removals only. • **Background**: In its Circular Economy Action plan in 2020, the European Commission announced its intention to develop a new certification scheme for carbon removal activities to ensure high quality of GGRs in the bloc, avoid greenwashing, and help it reach its climate targets. In November 2022, the Commission published its proposal for the EU CRCF, explaining how it envisions the new overall standard will work in the future. Consequently, an expert group of about 70 people across academia, businesses, NGOs, and public bodies was created to guide the Commission in designing specific methodologies for individual GGR technologies by late 2024. Currently, the EU CRCF is awaiting formal adoption by both the European Parliament and the Council, after which the Commission will adopt secondary legislation including implementing acts and delegated acts (for setting out specific methodologies).
GGR coverage	EU CRCF is being designed to accommodate three types of activities: (1) **carbon farming**, which includes nature-based GGRs, (2) **GGRs with permanent storage**, such as DACCS or BECCS, and (3) **carbon storage in products**, such as wood or concrete-based construction products. The exact list of GGR technologies allowed under the programme is expected to be finalised in 2024 as specific methodologies are developed by the Commission and the expert group.
Governance structure	• **The European Commission** is responsible for (1) establishing the specific implementation rules and methodologies for the CRCF (in consultation with the expert group), (2) evaluation and recognition of compliance of certification schemes with CRCF, (3) establishment and operation of a singular Union registry storing information on all issued credits, and (4) periodic review and update of CRCF (initially set for after 3 years). • **Certification schemes** (privately or publicly owned) will be responsible for registration of projects, sharing key project information with the Commission to maintain the Union registry, appointment / training of certification bodies and publication of annual summary reports. • **Member States** are responsible from accreditation and supervision of certification bodies, and running any public certification schemes they may want to establish.
Information rights	Since the EU is a public body, all underlying analysis and documentation associated with the CRCF is expected to be published and third parties would likely be able to draw inspiration from the programme. Considering the EU's history of expanding its emissions trading scheme (ETS) to non-EU countries, such as Switzerland, it may be possible for other countries to enter into a formal agreement with the EU to officially adopt the CRCF without significant financial contributions.
No of projects	Currently no projects are registered or credits issued under a certification framework following CRCF, since it is still under development.
Sustainability requirements	• GGR activities must have, at least, a neutral impact on climate change mitigation / adaptation, pollution prevention, circular economy, water / marine resources, food security, protection and restoration of biodiversity and ecosystems. Specific requirements will be determined by the methodologies. The requirements are expected to follow the technical screening criteria for Do Not Significant Harm, as laid under **Commission Delegated Regulation 2021/2139** and biomass sustainability criteria laid down in **Article 29 of Directive 2018/2001.** • Methodologies will encourage activities to provide additional co-benefits beyond the minimum sustainability requirements, which will be reported transparently on the certificates. The exact measurement and reporting requirements will be laid out in specific methodologies.
Key documents	• The original proposal for the EU CRCF – Link • Updated draft proposal for EU CRCF – Link • The impact assessment report – Link • Questions and answers for the EU CRCF – Link • Expert group on carbon removals – Link

Note: The EU CRCF is still a work in progress and most details are to be determined through future legislation. Information provided in this section represents our current best understanding of the scheme and is subject to change. Lack of detail on certain topics is due to lack of information in the proposal on those topics.

Overview: The EU Carbon Removal Certification Framework (2/2)

<table>
<tr><th colspan="2">MRV specifics</th></tr>
<tr><td>MRV and accounting basics</td><td>CRCF-aligned schemes will only certify net removals, which are calculated by subtracting project emissions from the gross removals. If project activities reduce existing carbon emissions, these are not accounted in the net removals calculations and are simply recorded as co-benefits of the credits, similar to other non-GHG co-benefits.
Baselines
• Standardised baselines will be developed to reflect the statutory and market conditions in the geographical context in which the carbon removal activity takes place. This will take into account carbon removal performance of comparable activities in similar social, economic, environmental, and technological circumstances. Inclusion of existing carbon removals in the baseline (mostly for carbon farming activities) is expected to simplify the additionality tests.
• The proposal suggest that baselines need to be periodically updated but the details are yet to be determined.
Additionality
• Activities must (1) not be required by existing regulations / laws and (2) must take place due to the incentive effect of the certification (financial test). Additionality can be assumed for activities that use standard baselines and remove more carbon than the baseline. Activities that opt for project-specific baselines will have to specifically meet the two additionality tests listed above.
• Certification schemes are required to share with the Commission all the necessary information about the credits they issue, so that a transparent public Union registry can be maintained to avoid double counting.
Permanence
• Projects will be required to monitor the storage sites throughout the monitoring period and take measures to mitigate risk of leakage.
• For carbon farming and carbon storage in long lasting products, carbon is assumed to be released back at the end of the monitoring period. For GGRs with permanent storage and carbon permanently chemically bound in products, removal is assumed to be permanent after liability is transferred to the relative public authorities in line with the EU CCS Directive (2009/31/EC).
• For activities falling outside of the EU CCS Directive, other liability measures should be employed, such as discounting, buffer pools or up-front insurance. There must always be a liable party at any time for the reversal of stored carbon. Further detail on liability provisions is to be determined.</td></tr>
<tr><td>Verification</td><td>• GGR operators (project developers) must submit an initial application to certification schemes. Upon approval, they must submit a comprehensive description of their processes and an estimation of removal volumes to an independent certification body. The certification body then performs a certification audit to verify the information and generates a report. After GGR project starts its operations, certification bodies must carry periodic re-certification audits to verify carbon removal volumes. Certification schemes should check all resulting audit reports and make their summary sections publicly available along with the certificates. Further details are to be determined by the Commission.
• Certification bodies are required to be accredited by the national accreditation authorities according to provisions set in Regulation (EC) No 765/2008 of the European Parliament and of the Council. Certification bodies must be fully independent of any GGR operator within this scheme and be supervised by Member States.</td></tr>
<tr><td>Treatment of uncertainty</td><td>CRCF requires quantification of carbon removals to account for and report uncertainties in accordance with recognised statistical approaches to limit the risk of over crediting. This accounting must be done in a conservative manner and be proportional to the level of uncertainty. Specific rules for addressing these uncertainties will be set in the specific methodologies.</td></tr>
</table>

Note: The EU CRCF is still a work in progress and most details are to be determined through future legislation. Information provided in this section represents our current best understanding of the scheme and is subject to change. Lack of detail on certain topics is due to lack of information in the proposal on those topics.

Expanding standards to new GGR technologies – EU CRCF

DACCS

Developing a new DACCS methodology is **not expected to be challenging** because:

- Provisions relating to storage of CO_2 can directly follow the national regulations based on the EU CCS Directive.
- Other aspects of a DACCS methodology, such as accounting for energy / chemical consumption and transportation of CO_2 well understood in the LCA literature.

ERW

Developing a new methodology for enhanced rock weathering is **expected to be significantly challenging** because:

- Existing methodologies do not have many common provisions with ERW activities.
- ERW still carries inherent uncertainties, which require continued experimentation and research to resolve.
- MRV protocols must rely on modelling to a degree, alongside additional field testing. To date, no ERW models have been fully validated.

BECCS

Developing a new BECCS methodology is **not expected to be challenging** because:

- Provisions relating to storage of CO_2 can directly follow the EU CCS Directive and accounting / rules around biomass supply may follow the RED II Directive.
- Remaining aspects, such as CO_2 transportation and treatment of co-products are well understood in the LCA literature due to precedence set in other sectors.

Buildings

Developing a new carbon negative building materials methodology is **expected to be moderately challenging** because:

- Existing EU legislation does not address this GGR technology.
- Original provisions need to be developed regarding accounting and measuring the exact amount of CO_2 stored in products, verifying source of CO_2, separation of carbon removals from emission reductions (via reduced cement demand), and tracking end use of building materials.

Biochar

Developing a biochar methodology is **expected to be moderately challenging** because:

- Existing RED II Directive provisions may help with drafting the sections on sourcing biomass, accounting for biomass emissions, and soil applications of biochar.
- However, drafting sections on ensuring permanence of removals, accounting for biochar decay, accounting of other pyrolysis co-products and tracking the end use of biochar may require some effort.

Oceans

Developing a new ocean removals methodology is **expected to be significantly challenging**

- EU CRFC would need to take a stance on non-geological or product forms of storage (i.e., DIC storage).
- Quantifying secondary impacts of ocean removals (i.e., calcification response, local ocean acidification reversal, etc) as part of sustainability requirements could prove difficult, as the secondary impacts are challenging to directly measure and would rely on significant modelling.
- Having a standardised baseline (i.e., non project-specific) would be challenging for ocean removals due to the diverse nature, scope, environments and impacts of expected projects.
- The liability requirements could be introduced to increase consumer confidence in credits.
- The requirement for intermittent recertification could be introduced.

Colour code: Green boxes – there is an existing / proposed methodology at least partially covering the GGR technology.

Frontier's MRV system aims to ensure long term robustness of GGR investments

General description	
Description and classification	• **Classification**: Frontier is an advanced market commitment, with a budget of over $1 billion, to purchase long term GGRs by 2030. Through selective impact investment strategies and a focus on MRV in the application process, Frontier aims to contribute to the GGR ecosystem by advancing MRV practices for engineered GGR technologies. • **Background**: Frontier was founded by Stripe, Shopify, Alphabet, Meta, and McKinsey in 2022 to aggregate the GGR demand these companies had. Frontier launched with an initial budget of just under $1 billion, however, soon expanded to have four more members. Between fall 2022 and June 2023, Frontier invested a total of $58.6 million to contract 121 ktCO_2 of GGR credits from 16 projects. • **Governance**: Frontier is a public benefit LLC wholly owned by Stripe Inc and it is run by a dedicated commercial and technical team. Its board consists of members from the five founding organisations. Frontier has a group of 9 advisers and 50+ technical reviewers from academic backgrounds who help develop its framework and aid project assessment processes.

GGR relevance	• Frontier exclusively operates in the **long-durability (>1,000 years) GGR space**, which includes most GGR technologies, excluding afforestation / reforestation, soil carbon removal, coastal restoration (blue carbon), and all emissions reductions projects.
	• Frontier has two tracks of GGR purchases:
	  ○ **Prepurchase**: Offers modest payments upfront to purchase small volumes through piloting new and innovative technologies.
	  ○ **Offtake**: Offers legally binding contracts to purchase larger volumes of GGR credits at an agreed price once removals are certified.

MRV and accounting basics	• **Uncertainties & accounting**: Frontier requires all applicants to estimate net removals through quantifying project emissions by an LCA. Project developers are also required to quantify uncertainty components of their projects following the steps / processes listed in the GGR verification framework developed by Carbon Plan. Projects with relatively high uncertainties are only considered for prepurchase, while projects with higher confidence levels can be consider for larger offtake agreements. Frontier applies a discount rate to GGR volumes equal to the total quantified uncertainty. For example, if a project has 30% uncertainty, each tonne of carbon removal generates 0.7 credits. • **MRV**: Suppliers are required to describe their intended MRV approaches in their applications. This may be higher level for prepurchase, but offset agreements require disclosing a full independently developed certification methodology (either using an existing methodology or developing a new methodology). Frontier contracts usually include various milestones to unlock future purchases and some of these relate to reduction of MRV costs or accounting uncertainties, for example through verification of models or deployment of novel measurement instruments. • Frontier requires methodologies to **ensure durability of removals** through (1) proper monitoring protocols to detect any leakage or reversal, and (2) determining appropriate thresholds and requirements to assume "functional stability" of the stored CO_2, after which monitoring can stop.
Crediting	• Frontier requires projects to get third party certification using a methodology approved by itself in the application process. GGR credits must be listed in a public registry. Frontier does not have a list of pre-approved independent verifiers or standards but requires methodologies to be developed by independent scientific advisory, clear separation between standards and marketplaces, and clear distinction of GGR and emissions reduction credits. • Frontier also displays all contracted companies on its website, disclosing some key information, such as purchase volume, price, project description, etc. For earlier projects, this included the full application, but Frontier will be selectively sharing information going forward to protect applicants' IP.
Key documents	• Frontier webpage – Link • Frontier Supplier CDR Measurement & Verification Q&A – Link • Frontier GitHub source materials – Link

GHG Protocol for Project Accounting ("Project Protocol") discusses methods for quantifying and reporting project-based GHG reductions

<table>
<tr><th colspan="2">General description</th></tr>
<tr><td>Description and classification</td><td>Classification: The GHG Protocol has established comprehensive global standardized frameworks to measure and manage GHG emissions from private and public sector operations, value chains and mitigation actions. This slide focuses on the 'Project Protocol' standard.
Background: The 'project Protocol' standard provides specific principles, concepts, and methods for quantifying and reporting GHG reductions—that is, the decrease in GHG emissions, or increase in removals and/or storage—from climate change mitigation projects (also referred to as 'GHG projects' by the Project Protocol). The standard was developed by the GHG Protocol in 2005 following a dialogue and consultation process with business, environmental, and government experts led by WRI and WBCSD. No updates have been made to the standard since its publication.
Governance: GHG Protocol convenes governance bodies that guide the development of its accounting and reporting standards. The governance bodies include an Advisory Group, Technical Working Groups, Review Group, Pilot Testing Group, and the Secretariat.</td></tr>
<tr><td>GGR relevance</td><td>The standard is broadly applicable to all types of GHG projects, including GHG removals and/or storage.</td></tr>
<tr><td>MRV and accounting basics</td><td>Baselines – The standard presents two procedures for estimating baseline emissions associated with a project activity's primary effect (intended change caused by a project activity in GHG emissions, removals, or storage associated with a GHG source or sink):
Project-specific procedure: Baseline emissions are estimated by identifying a baseline scenario specific to the proposed project activity. Estimated emissions are valid only for the project activity being examined.
Performance standard procedures: Baseline emissions estimates are produced using a GHG emission rate derived from a numerical analysis of the GHG emission rates of all baseline candidates. Baseline candidates refer to alternative technologies or practices, within a specified geographic area and temporal range, that could provide the same product or service as a project activity.
For each project activity, primary effect and significant secondary effect (unintended change caused by a project activity in GHG emissions, removals, or storage associated with a GHG source or sink), the valid time length for corresponding baseline scenario or performance standard needs to be identified. GHG reductions should be quantified for a period of time no longer than the shortest valid time length identified. Calculation methods used to quantify GHG reductions and any uncertainties associated with project activity GHG emission estimates should be documented.
Additionality – The standard does not require a demonstration of additionality per se. Additionality is incorporated as an implicit part of the procedures used to estimate baseline emissions, where its interpretation and stringency are subject to user discretion.
MRV – The standard describes the data that need to be monitored in order to credibly quantify GHG reductions. It contains minimum requirements for reporting GHG reductions in a manner that is transparent and allows for evaluation by interested parties. However, the standard does state verification as a requirement nor does it offer guidance on how to solicit or conduct third-party verification.</td></tr>
<tr><td>Crediting</td><td>The Project Protocol acknowledges the role of GHG reduction credits in meeting emissions targets. However, the issuance of credits is beyond the scope of the standard as the GHG Protocol does not have its own registry. Furthermore, it does not recommend any carbon credit schemes.</td></tr>
<tr><td>Key documents</td><td>GHG Protocol for Project Accounting – <u>Link</u>
GHG Protocol Governance process - <u>Link</u></td></tr>
</table>

GHG Protocol Land Sector and Removals Guidance will serve as a guide for companies that choose to report carbon removals

General description	
Description and classification	• **Classification**: The GHG Protocol has established comprehensive global standardized frameworks to measure and manage GHG emissions from private and public sector operations, value chains and mitigation actions. This slide focuses on the Land Sector and Removals Guidance (Draft for Pilot testing and Review). • **Background**: The guidance explains how companies should account for and report GHG emissions and removals from land management, land use change, biogenic products, carbon dioxide removal technologies, and related activities in GHG inventories, building on the GHG Protocol's Corporate Standard and Scope 3 Standard. The guidance can be used by any organisation that has land sector activities or CO_2 removals and storage within its operations or value chain. As per the guidance, reporting removals will be optional. **Note:** This guidance has been in development since 2020 and is expected to be finalised in 2023. • **Governance**: GHG Protocol convenes governance bodies that guide the development of its accounting and reporting standards. The governance bodies include an Advisory Group, Technical Working Groups, Review Group, Pilot Testing Group, and the Secretariat.
GGR relevance	• The guidance includes an overview of GHG mitigation and removal enhancement opportunities such as BECCS, DACCS, biochar addition to soil, and incorporating atmospheric carbon into long-lived products and/or materials through technological solutions. • There is guidance on accounting for life cycle CO_2 emissions and removals associated with biogenic or technological CO_2 removal (TCDR) carbon cycle pathways, including geological storage, but not for that associated with ocean or freshwater-based carbon pools.

MRV and accounting basics	• **MRV** – Ongoing carbon storage monitoring should be specified through a **monitoring plan**, to demonstrate that the carbon remains stored or to detect losses of the stored carbon. Companies can account for and report removals only if the reporting company has **traceability** throughout the full CO_2 removals pathway, including to the sink, to the carbon pools where the carbon is stored, and to any intermediate processes if relevant. If companies lose the ability to monitor carbon stocks associated with previously reported removals, then companies must assume previously reported removals are emitted and report reversals. The same requirements apply when companies account for net carbon stock changes of biogenic and TCDR-based products sold by the reporting company.
	• Companies must account for all GHG emissions that occur in the life cycle of products and report them as scope 1, scope 2, or scope 3 emissions (by scope 3 category), excluding gross CO_2 emissions from the biogenic or TCDR carbon content of products. For gross CO_2 emissions from the biogenic or TCDR carbon content of products, companies shall:
	    • Account for all direct and indirect gross CO_2 emissions across the life cycle, including end-of-life treatment, and
	    • Separately report these emissions under the Gross emissions and gross removals category, as Gross biogenic product CO_2 emissions or Gross TCDR-based product CO_2 emissions (if applicable), organized by the relevant scope 1, scope 2 or scope 3 categories to differentiate direct from indirect emissions.
	• **Uncertainty -** Companies can account for and report removals only if these are statistically significant and companies provide quantitative uncertainty estimates for removals, including 1) the removal value, 2) the uncertainty range for the removal estimate based on a specified confidence level, and 3) justification of how the selected value does not overestimate removals.

Crediting	The guidance is for companies to compile and report their annual GHG inventory and track performance over time. It states that, "The focus of the guidance is therefore on GHG inventory accounting rather than project accounting or GHG crediting.
Key documents	Part 1 - Accounting and reporting requirements and guidance (Link) Part 2 – Calculation guidance (Link)

The IPCC's Working Group III report on Mitigation of Climate Change emphasises the importance of GGR technologies and lack of robust MRV methodologies

General description	
Description and classification	• **Classification**: The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. In 2022, the IPCC published the Working Group III report on Mitigation of Climate Change that discusses Carbon Dioxide Removal (CDR) methods, including engineered solutions. • **Background**: This report was prepared and published by the IPCC in 2022. The IPCC is an independent body founded under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). It provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. • **Governance**: The IPCC currently has 195 member countries. For the assessment reports, experts volunteer their time as IPCC authors to assess thousands of scientific papers published each year to provide a comprehensive summary of what is known about the drivers of climate change, its impacts and future risks, and how adaptation and mitigation can reduce those risks. An open and transparent review by experts and governments is an essential part of the IPCC process, to ensure an objective and complete assessment and to reflect a diverse range of views and expertise.
GGR relevance	• The IPCC report defines and discusses Carbon Dioxide Removal (CDR) methods. CDRs refer to anthropogenic activities removing CO_2 from the atmosphere and storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities. Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to fossil CO_2 do not count as removal technologies. CCS and CCU can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air, and stored in geological reservoirs or products. This is what differentiates CDRs from what is referred to as GGRs in this study. • Engineered CDRs discussed include biochar, DACCS, BECCS, enhanced weathering • The report summarises the following for each of the CDR methods: TRL level, costs, mitigation potential; risks and impacts; co-benefits; trade-offs and spill over effects; and role in mitigation pathway. • The illustrative mitigation pathways (IMPs) assessed in the report use land-based biological CDR (primarily afforestation/reforestation (A/R)) and/or BECCS). Some also include DACCS.
MRV and accounting basics	• The report does not specify any MRV or accounting methodologies. It states that to accelerate research, development, and demonstration, and to incentivise CDR deployment, a political commitment to formal integration into existing climate policy frameworks is required, including reliable measurement, reporting and verification (MRV) of carbon flows.
Crediting	• This is beyond the scope of the IPCC report. Furthermore, the IPCC does not maintain a registry nor does it recommend any carbon credit schemes.
Key documents	Mitigation of Climate Change (Technical Summary) - Link Mitigation of Climate Change (Full Report) - Link

The Oxford Principles for Net Zero Aligned Carbon Offsetting ("Oxford Offsetting Principles") recommend carbon removal offsets over emission reduction offsets

General description	
Description and classification	• **Classification**: The Oxford Offsetting Principles outline four principles for credible net zero-aligned carbon offsetting. The principles serve as a guide for the design and delivery of voluntary net-zero commitments by government, cities and companies, and provide a framework for supporting the growth of the carbon market. • **Background and governance**: The Oxford Offsetting Principles were developed in 2020 by a multi-disciplinary team at University of Oxford. The team included experts associated with the Smith School of Enterprise and the Environment, Environmental Change Institute, Oxford Martin School, Blavatnik School of Government, Saïd Business School, and the Nature-based Solutions Initiative at the Department of Zoology.
GGR relevance	• Principle 2 recommends offset buyers to increase demand for carbon removal offsets generated by projects such as biological carbon sequestration, BECCS, DACCS or geological storage of carbon. The message is reinforced in Principle 4 on supporting the development of net zero-aligned offsetting.
MRV and accounting basics	• **Additionality –** Principle 1 recommends carbon offset buyers to use offsets that are additional and acknowledges the difficulty in determining and verifying additionality. • **Permanence** – The concept of permanence is defined in Principle 1 and emphasised by Principle 3 which recommends an offsets portfolio that increases the portion of carbon removals over emission reductions, and the portion of long-lived storage over short-lived storage. • **MRV –** Principle 1 recommends buyers to use offsets that are verifiable and correctly accounted for, have a low risk of non-additionality, reversal, and creating negative unintended consequences. However, it does not specify MRV practices or tool. • The principles do not provide any guidance on establishing project baseline emissions and/or conducting an LCA.
Crediting	• This is outside the scope of the report.
Key documents	The Oxford Offsetting Principles - Link

CORSIA is the current global mechanism for GHG reduction in aviation *(1 of 2)*

General description	
Description and classification	• **Classification**: The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global offsetting scheme whereby airlines and other aircraft operators must offset any growth in CO_2 emissions above a 2019 (pre-COVID) baseline. Airlines can comply with CORSIA through a number of measures, including using fuel with lower CO_2 emissions, and buying emissions offsets. • **Background**: The CORSIA offsetting scheme was adopted by the Council of the International Civil Aviation Organization (ICAO) on 27 June 2018, became effective on 22 October 2018 and applicable on 1 January 2019. CORSIA is being implemented in three phases: a pilot phase (2021-2023), a first phase (2024-2026), and a second phase (2027-2035). For the first two phases, participation is voluntary. From 2027 onwards, participation will be determined based on 2018 RTK data (Revenue Tonne Kilometres). As of 1 January 2023, 115 countries had announced their intention to participate in CORSIA. 6 more countries announced their intention to participate in CORSIA from 1 January 2024, bringing the total number of participating countries to 121. • **Governance**: ICAO is funded and directed by 193 national governments to support their diplomacy and cooperation in air transport as signatory states to the Chicago Convention (1944). Its core function is to maintain an administrative and expert Secretariat of international civil servants supporting these diplomatic interactions, and to research new air transport policy and standardization innovations. Industry, civil society groups, other regional and international organizations, also participate in the development of new standards at ICAO. As new priorities are identified by these stakeholders, the ICAO secretariat convenes panels, task forces, conferences and seminars to explore their technical, political and socio-economic aspects. It then provides governments with the best results and advice possible as they collectively and diplomatically establish new international standards and recommend practices for civil aviation. Once governments achieve diplomatic consensus around a new standard's scope and details, it is then adopted by the member countries.
GGR relevance	• CORSIA does not have any specific provisions for GGRs. However, it does specify that carbon offset credits must represent emissions reductions, avoidance, or carbon sequestration that are permanent (see section on MRV).
MRV and accounting basics	• **Baselines –** The baseline emissions vary depending on the CORSIA phase. For the pilot phase (2021-2023) the baseline is the total emissions covered by CORSIA in 2019. For the first and second phases (2024-2035), the baseline will be 85% of the total CO_2 emissions covered by CORSIA in 2019. • **Additionality** – The CORSIA Emissions Unit Eligibility Criteria document states that carbon offset programs must generate units (credits) that represent emissions reductions, avoidance, or removals that are additional. Eligible offset credit programs should clearly demonstrate that the programme has procedures in place to assess/test for additionality and that those procedures provide a reasonable assurance that the emissions reductions would not have occurred in the absence of the offset program. For the CORSIA compliance period 2021-2023, 4 of the schemes covered in this study are included, namely American Carbon Registry, Climate Action Reserve, the Gold Standard, and Verified Carbon Standard (VCS). For the 2024 -2026 Compliance Period, only American Carbon Registry and Architecture for REDD+ Transactions (not covered in this study) are included in the list. • **Permanence** – The CORSIA Emissions Unit Eligibility Criteria document states that carbon offset credits must represent emissions reductions, avoidance, or carbon sequestration that are permanent. If there is risk of reductions or removals being reversed, then either (a) such credits are not eligible or (b) mitigation measures are in place to monitor, mitigate, and compensate any material incidence of non-permanence. • CORSIA's MRV system focuses on GHG reductions through fuel substitution, and does not cover GGRs.

CORSIA is the current global mechanism for GHG reduction in aviation *(2 of 2)*

General description	
Crediting	• Aircraft operators should use only eligible emissions units for the purpose of meeting their offsetting requirements under CORSIA. CORSIA eligible emissions units for the 2021-2023 compliance period by programme such as American Carbon Registry are listed in the document referred to above. • The carbon scheme/programme must provide for and implement its registry system to identify its CORSIA eligible emissions units, and to enable the public identification of cancelled units that are used toward CORSIA offsetting requirements, if the registry does not already feature this capability. This should be done consistent with the capabilities described by the programme in its communications with ICAO, and any further requirements decided by the ICAO Council for CORSIA Eligible Emissions Unit Programme-designated Registries. • An aircraft operator can implement emissions reduction project that generates emissions units. These need to be CORSIA eligible emissions units that meet the CORSIA Emissions Unit Eligibility Criteria, if the operator wishes to use the units to fulfil its offsetting requirements under CORSIA. **Note**: Projects that reduce emissions from international flights would not be eligible to be used under CORSIA as this would result in double counting of emissions reductions.
Key documents	CORSIA main document (Link)

ISO 14040/44 standards describe the principles, framework, and requirements for LCAs

General description	
Description and classification	• **Classification**: ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) while the ISO 14044:2006 specifies requirements and provides guidelines for LCA. • **Background**: The ISO 14040/44 standard has been developed by the ISO (International Organization for Standardization) which is an independent, non-governmental international organization with a membership of 168 national standards bodies. ISO 14040 and 14044 standards were originally published in 1997 and 2006 respectively in various carbon credit schemes[1]. The standards have been reviewed in 5-year intervals with the last update in 2006 and latest review in 2022 (Reviewed and confirmed. 2006 version of both standards remain valid.). • **Governance**: Through its members, the ISO brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards.
GGR relevance	• The ISO 14040/44 standards cover general principles and requirements for LCAs which could serve as guidelines for GHG projects including those applying GGR technologies. There is nothing specific on GGRs in either standard.
MRV and accounting basics	• ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA) including definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA. • **MRV and Additionality –** These are not covered in ISO 14040/44 standards. They are addressed in the ISO 14064-2 and ISO 14064-3 standards. See slide on ISO 14060 family of standards (following slide). • **Accreditation –** This is not covered in ISO 14040/44 standards as it is the focus of another standard, the ISO 14065. See slide on ISO 14060 family of standards (following slide).
Crediting	• The certification and crediting process is not in scope of the ISO 14040/44 standards. **These standards are not intended for contractual or regulatory purposes or registration and certification.**
Key documents	ISO 14040:2006 overview - Link ISO 14044:2006 overview - Link ISO 14065:2020 overview - Link

ISO 14060 family of standards address the issue of consistency for quantifying, monitoring, reporting and validating or verifying GHG emissions and removals

General description	
Description and classification	• **Classification**: The ISO 14060 family of standards aims to provide clarity and consistency for quantifying, monitoring, reporting and validating or verifying GHG emissions and removals to support sustainable development via low-carbon economy. The key standard of interest for this study is the ISO 14064-2:2019 which is an international standard that provides guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. It should be noted that this standard contains general requirements for GHG projects and does not prescribe specific criteria and procedures. The remaining slide focuses on this standard and its inter-linkages with other standards in the ISO 14060 family of standards. • **Background**: The ISO 14064-2 standard has been developed by the ISO (International Organization for Standardization) which is an independent, non-governmental international organization with a membership of 168 national standards bodies. ISO 14064-2 has been in use since it was originally published in 2006 in various carbon credit schemes[1]. The standard has been reviewed in 5-year intervals with the latest update in 2019. • **Governance**: Through its members, the ISO brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards.
GGR relevance	• ISO 14064-2 contains general principles which would be applicable to all GHG projects including those applying GGR technologies.
MRV and accounting basics	• ISO 14064-2 standard requires project proponents to identify and select GHG sources, sinks and reservoirs relevant to the GHG project and to determine the GHG baseline. GHG project emissions/removals and baseline scenario emissions/removals should be quantified separately. Emission reduction and/or removal enhancements should be calculated by comparison of the GHG project emissions/removals with that of the baseline scenario. Project proponents need to demonstrate that the GHG baseline meets the standard's principles of conservativeness and accuracy, so that results reported are credible and not over-estimated. For both project emissions ad baseline scenario, the quantification, monitoring and reporting of GHG emissions and removals will be based on procedures developed by the project proponent or adopted from a GHG offset/crediting programme. • **Additionality** – ISO 14064-2 requires that a GHG project should result in emission reductions or removal enhancements in addition to what would have happened in the absence of the project. However, the standard leaves specific criteria and requirements related to additionality to individual GHG offset/crediting programmes. • **Validation/ verification** – ISO 14064-2 does not specify requirements for verification/ validation bodies (VVBs) or verifiers/ validators in providing assurance against GHG statements or claims by GHG projects. Such requirements may be specified by individual GHG offset/crediting programmes or can be found in ISO 14064-3 standard. ISO 14064-3 details requirements for verifying GHG statements related to GHG inventories, GHG projects, and carbon footprints of products. It describes the process for verification or validation, including verification or validation planning, assessment procedures, and the evaluation of organisational, project and product GHG statements. • **Accreditation** – This is not covered in ISO 14064-2 as it is the focus of another standard, the ISO 14065. ISO 14065 defines requirements for VVBs, and can be used as a basis for accreditation. The standard's requirements cover impartiality, competence, communication, validation and verification processes, appeals, complaints, and the management system of validation and verification bodies.
Crediting	• The certification and crediting process is not included in the ISO 14064-2 standard. This is covered by individual GHG offset/crediting programmes.
Key documents	ISO 14064-2:2019 overview – Link ISO 14064-3:2019 overview - Link ISO 14065:2020 overview - Link

The Integrity Council for the Voluntary Carbon Market has defined principles and a CORSIA-linked assessment framework for carbon-crediting programmes *(1 of 2)*

General description	

Description and classification	• **Classification**: The Integrity Council for the Voluntary Carbon Market (ICVCM) aims to set and maintain a voluntary global threshold/benchmark standard for quality in the voluntary carbon market based on the 10 **Core Carbon Principles (CCPs**). These are fundamental principles for high-quality carbon credits that create real, verifiable climate impact, based on the latest science and best practice. ICVCM's **Assessment Framework** sets out the detailed criteria it will use to assess whether carbon-crediting programmes and categories of carbon credits meet these requirements. Carbon-crediting programmes that meet the CCP criteria will be able to apply the CCP label to credits from categories that meet the criteria. ICVCM considers ICAO's CORSIA scheme assessment criteria, along with other criteria, in its assessment framework. CORSIA-approved carbon-crediting programmes do not have to demonstrate to ICVCM that they meet CORSIA requirements. This can fast-track ICVCM certification and approval process for such programmes.
	• **Background**: ICVCM is an independent governance body for the voluntary carbon market. In March 2023, ICVCM released the final version of the CCPs and associated documents:
	    • The Programme-level Assessment Framework, setting out the detailed criteria to assess whether carbon-crediting programmes meet the CCPs;
	    • The Assessment Procedure, explaining its process for implementing the CCP label in the market;
	    • CCP Attributes, which are tags programs can apply to highlight additional quality features of CCP-labelled carbon credits.
	• **Governance**: The Integrity Council comprises experts in climate science and academia, sustainable finance, carbon market methodologies, NGOs, UNFCCC process, policy and regulation. The council also comprises of members from the corporate sector, Indigenous Peoples and local communities.

GGR relevance	• If a carbon-crediting programme chooses to become ICVCM-approved or CCP-eligible, then ICVCM's principles and criteria will be applicable to certification of GHG projects registered with that programme, including those applying GGR technologies.

MRV and accounting basics (1 of 2)	• Principle 7 of the CCPs requires robust **quantification** of GHG emission reductions and removals. ICVCM's assessment framework has detailed criteria to assess compliance of programmes with these requirements, including:
	    • Methodology approval process including processes prior to approval, periodic review and suspension and/or withdrawal of methodologies which may be leading to overestimation of GHG reductions/removals or where additionality may not be ensured. ICVCM plans to include a minimum elapsed time for the review of methodologies by carbon-crediting programmes.
	    • Quantifying GHG emission reductions or removals: Each programme should have requirements such as defining the length of crediting period, ensuring conservativeness of quantification methodologies, and assessment of uncertainties of GHG reductions/removals.
	    • Ex-ante carbon credits are not CCP eligible. Ex-ante credits represent intended emission reductions. Also referred to as forward crediting, meaning an avoidance or removal activity will occur in the future or is yet to be verified. Entities have to wait for these credits to be verified in order to claim them in their carbon footprint offsetting.
	• **Additionality** – Principle 5 of the CCPs requires GHG emission reductions or removals from the mitigation activity to be additional. This needs to be explained in the mitigation activity design document (see point on Principle 3 below).

The Integrity Council for the Voluntary Carbon Market has defined principles and a CORSIA-linked assessment framework for carbon-crediting programmes *(2 of 2)*

General description	

MRV and accounting basics (2 of 2)	• **Permanence** – Principle 6 of the CCPs requires GHG emission reductions or removals from the mitigation activity to be permanent or, where there is a risk of reversal, there should be measures in place to address those risks and compensate reversals.
	• Principle 3 requires these programmes to provide **transparent** and publicly available information on all credited mitigation activities. This includes:
	    • spreadsheets used for GHG reduction calculations,
	    • a mitigation activity design document that has a non-technical summary as well as information on the mitigation technology/practice applied and the methodology used to calculate baseline emissions and GHG reductions or removals.
	• Principle 4 of the CCPs requires carbon-crediting programmes to have programme-level requirements for third-party **validation and verification** of mitigation activities. In addition to CORSIA requirements, the carbon-crediting programmes should:
	    • require VVBs to be accredited by a recognised international accreditation standard (e.g., ISO 14065 and ISO 14066, or per rules relating to the UNFCCC Kyoto Protocol Clean Development Mechanism or Paris Agreement Article 6, paragraph 4 Supervisory Body)
	    • have a process for managing VVB performance, and to address performance issues including measures to ensure that poor VVB performance is reported to the relevant accreditation body, and provisions to suspend or revoke the participation of a VVB in the programme.

Crediting	• Principle 2 of the CCPs requires carbon-crediting programmes to operate or make use of a registry to uniquely identify, record and track mitigation activities and carbon credits issued. In addition to CORSIA requirements related to carbon credits in the carbon-crediting programme registry, the carbon-crediting programme should:
	    • require identification of the entity on whose behalf the carbon credit was retired.
	    • require the identification of the purpose of retirement.
	    • have procedures to address erroneous issuance of carbon credits that identify remedial measures and the entities responsible for implementing these
	• As mentioned previously, carbon-crediting programmes that are deemed CCP-eligible will be allowed to apply the CCP label to credits from categories that meet the criteria.

Key documents	ICVCM Core Carbon Principles - Link

Microsoft's criteria for high-quality carbon removal, used in their annual CDR credit procurement

General description	
Description and classification	• **Classification and Background**: Microsoft has pledged to reduce its value-chain GHG emissions by >50% by 2030, remove the remaining emissions, and then remove the equivalent of its historical emissions by 2050. Microsoft plans to do this through procuring high-quality GGRs and investing in CDR technologies. Microsoft worked with Carbon Direct to develop a common framework by which these high-quality GGRs would be assessed. The organisations released their updated assessment criteria for Microsoft's 2023 Procurement Cycle in 2022, with projects without credits available within FY2023 able to apply on a rolling basis. • **Governance**: Microsoft and Carbon Direct review each proposal for all prerequisites and criteria through a two-step application process. First, they conduct a prerequisite review which encompasses all prerequisites mentioned in the guidance and criteria documents. When a project meets the minimum prerequisites, it moves to the due diligence phase. This includes a secondary application to further investigate how the project meets the specifications laid out in the criteria for high-quality carbon removal.
GGR relevance	• The 2023 assessment criteria outlines standards for both nature based GGRs (forestry and agroforestry, mangrove forestation, improved forest management, soil carbon) and engineered GGRs (biomass-based pathways, carbon mineralisation and direct air capture).

MRV and accounting basics (1/2)	• **Prerequisites and considerations**: In addition to the specific criteria for each eligible GGR tech Microsoft places special emphasis on projects with a proven net negativity (on a lifecycle basis), scientific verification (comprehensive independent review) and environmental justice (avoiding or minimising economic, environmental or social harm). Additional priority is placed on projects with global CDR potential, has a pathway to affordability (i.e., \$100/tCO_2 in 5-10 years), technology innovation (improves carbon market outcomes) pursues co-benefits (social and/or environmental) and has other sustainability dimensions (i.e., promotes water stewardship, waste reduction, biodiversity, etc). Durability is generally split between "low" (100 years), "medium" (1,000 years) and "high" (thousands of years). However, each GGR technology has its own additional durability considerations and requirements.
	• Each GGR tech has requirements ("projects must") and recommendations* ("projects should"). The minimum requirements are detailed as follows:
	• **Biomass-based pathways criteria (BECCS, biochar, etc)**
	    • **Additionality and baselines:** projects must identify the fate of biomass resources, the counterfactual for the biomass used, and explain the economic viability of the project with or without the requested investment (including role of relevant tax and policy incentives)
	    • **Carbon accounting method:** projects must prove carbon negativity on a cradle-to-grave LCA (including biomass, CO_2 and product transport) and for waste feedstocks they must provide counterfactuals.
	    • **Harms and benefits:** projects must show that feedstock production, biomass conversion, and carbon disposal operations have a low risk of any materially negative impacts on the surrounding ecosystems
	    • **Durability:** projects using geologic storage must use established permitting processes (i.e., Class VI) or alternatively meet ISO 27914:2017 standard for CO_2 storage.
	    • **Environmental justice:** projects must show that they engage local communities, from feedstock production to energy conversion to carbon transport and disposal, in an ongoing and transparent manner throughout the project lifetime and adopt best practices for engagement.
	    • **Leakage:** projects must quantify the likely carbon emissions that result from their project's consumption or displacement of local and regional energy supplies, such as that which might result from the parasitic load for capture and compression of CO_2.
	    • **Other:** projects must ensure reliable feedstock availability over the project lifetime and verify that biochar applications do not lead to rapid return of carbon to the environment.

*Note that although recommendations are not explicitly covered in this report, some may be influential for specific GGR technologies applying for procurement, as the recommendations can be much more quantitative rather than the requirements which are generally more qualitative. For example, the DAC recommendation is that project life cycle emissions are less than 0.3/tCO_2e emitted per tCO_2 removed from air.

Microsoft’s criteria for high-quality carbon removal, used in their annual CDR credit procurement

General description	

MRV and accounting basics (2/2)	• **Carbon mineralisation**
	  • **Additionality and baselines:** projects must quantify additionally that include carbon in solid, liquid and gas form, metals that contribute to mineral carbonate formation, and alkalinity imported into or exported from the project boundaries. Projects must also quantify naturally occurring rates of weathering and mineralisation, and the naturally occurring carbonate mineral content in feedstocks.
	  • **Carbon accounting method:** Projects must use the best available measurement methods with built-in redundancy to measure carbon contents and fluxes, compare upfront carbon emissions associated with project development against carbon uptake annually and over the project lifetime, and evaluate and monitor, where appropriate, the impact of the project on other GHG pathways.
	  • **Harms and benefits:** defers to the prerequisites
	  • **Durability:** no requirements, only recommendations (i.e., “projects should”)
	  • **Environmental justice:** projects must avoid disturbance of land that has been identified as culturally sensitive or ecologically important by community stakeholders.
	  • **Leakage:** no requirements, only recommendations (i.e., “projects should”)
	  • **MRV:** projects must supplement modelling with direct measurement of mineralisation rates and amounts, as well as include quantification of carbonate mineral content in feedstock baseline data.
	  • **Other:** no requirements, only recommendations (i.e., “projects should”)
	• **Direct air capture**
	  • **Additionality and baselines:** projects must clearly demonstrate that increased air capture tonnage would not happen in the absence of the project or carbon income, and include quantification of baseline GHG fluxes and any GHG fluxes associated with energy consumption, site preparation, and carbon storage/utilisation.
	  • **Carbon accounting method*:** projects must clearly document all aspects of the life cycle GHG emissions of the project, including ongoing measurement and reporting of removed and stored CO2, and include all sources of emissions through the entire project’s life cycle.
	  • **Harms and benefits:** no requirements, only recommendations (i.e., “projects should”)
	  • **Durability:** projects must demonstrate sufficient CO2 storage capacity identified and booked for the full project lifetime, or access to sufficient CO2 storage elsewhere with credible CO2 transport options to the locations, sufficient injectivity at storage site, and low risk for CO2 release.
	  • **Environmental justice:** projects must avoid disturbance of land that has been identified as culturally sensitive or ecologically important by community stakeholders.
	  • **MRV:** projects must present a valid MRV plan that **adheres to key regulatory requirements for CCUS activities** (i.e., Class VI permits)
	  • **Other:** projects must demonstrate process inputs have a low operational safety risk, provide a descriptions of low carbon energy supply, demonstrate displacement of high carbon-intensity products or processes for projects involving CO2 reduction in combinations with DAC utilisation, present valid costs estimates, test thermal and electrical energy supplies to match theoretical requirements, demonstrate ability to manufacture or procure proposed design components, and ensure a viable low-carbon energy supply at large scale.

Key documents	• Criteria for high-quality CDR (FY 2023) – Link • Guidance document: Microsoft CDR procurement cycle – Link • Microsoft Carbon Removal: Observations from third year - Link

*Note that although recommendations are not explicitly covered in this report, some may be influential for specific GGR technologies applying for procurement, as the recommendations can be much more quantitative rather than the requirements which are generally more qualitative. For example, the DAC recommendation is that project life cycle emissions are less than 0.3/tCO2e emitted per tCO2 removed from air.

Shopify has developed a public "playbook" that is uses when evaluating GGR investment opportunities and purchasing credit removals through the Shopify Sustainability Fund

General description	
Description and classification	• **Classification**: Shopify has published a "Playbook" which lies out the critical considerations it gives to evaluating GGRs when purchasing credits or investing in projects. • **Background**: Shopify is an e-commerce platform for online stores and retail point-of-sale systems. It is active in the carbon removals space by acting as a credit purchaser (through the Shopify Sustainability Fund, an advanced market commitment which helped found Frontier - see previous slide), and through providing guidance on how other companies can develop their own purchasing standards (Shopify Carbon Removal Buying Guide). The Buying Guide has a number of "non-negotiable" criteria (net negativity, verifiability, additionality, safety/environmental justice), criteria that are "critical for consideration" (cost close to $100/tCO2 at scale, durability of >100 years, capacity), and criteria that are extra (specific to buyer). • **Governance**: Shopify evaluates their own criteria through their "Playbook" which (in conjunction with the criteria set through Frontier) governs their carbon removal purchases made by the Shopify Sustainability Fund.
GGR relevance	• Shopify has used their Playbook to invest in engineered GGRs ranging from ocean removals, mineralisation, products (concrete), DACCS, BECCS and potentially biochar.
MRV and accounting basics	• **Long-term atmospheric removal**: Shopify requires a minimum threshold for long-term storage of 100 years. While Shopify has prioritised carbon removals, it has also purchased avoided emissions offsets (where CO_2 is prevented from entering the atmosphere) or reduced emissions offsets (where CO_2 emissions are reduced due to process changes or material substitution) in a few cases where they felt their purchase would help that technology develop into a true carbon removal. • **Prepay:** Shopify prepaid for carbon removals from companies with solutions and technologies which were not commercially available (i.e., seeking seed or Series A funding). • **Long-term agreements:** Shopify committed to multi-year purchase agreements (i.e., 5-year terms with additional 5-year option) to provide GGR companies with a reliable cash flow for several years. • **LCA:** Shopify requires that each company submits an LCA. However, for more early-stage companies, Shopify relied on scientific literature and advice from experts in the field to evaluate the potential removal capacity of the solution. Projects with no LCA were given removal purchase agreements for research projects to prove/disprove estimated removal capacity. Shopify recommends use of industry standard tools and consulting widely with industry and scientific experts when reviewing LCA. • **MRV:** Shopify were comfortable with investing in storage mechanisms which relied on "well-understood chemical reactions" (i.e., incorporation of CO2 into concrete or reactive rock formations) with the Shopify expectation that monitoring will be more straightforward. Where available, Shopify relies on standard protocols (referenced in individual contracts). In all cases, contracts include requirements for companies to submit monitoring and verification data and evidence that the carbon was stored. MRV is reviewed based on a matrix of Performance Criteria and Indicators (see following slide).
Crediting	• Shopify customised each contract and developed both prepayment and multi-year agreement options. • For commercially available solutions, Shopify includes more stringent expectations due to companies already having de-risked their technologies. These contracts include standard payment structures where Shopify is invoiced for services once completed, performance requirements, and penalties (such as refunds) for missed deliveries. • For companies in research and pilot stages, the contracted amount of carbon to be removed is an estimate that may not be achieved. Rather than requiring companies to provide a refund, Shopify included options to extend the delivery time period or to adjust the price per tonne upwards.
Key documents	• Shopify Sustainability Fund – Link • Shopify Carbon Removal Buying Guide – Link • Shopify Carbon Removal Playbook – Link

Shopify uses a matrix of Performance Criteria and Indicators to evaluate MRV and operational performance of GGR projects

Performance Criteria and Indicators

	Objective	Example Indicators	Target	Year 1	Year 2	Year 3	Year 4	Year 5
Milestones and Execution	Contract requirements are met	Ordering, invoicing, and billing carried out in accordance with contract timelines	100%					
		Services completed and certified (if appropriate) within contract timelines	100%					
		All postponements/delays reported within contract timelines	100%					
		All reporting and documentation requirements completed	100%					
	Project and construction milestones are met	Financing secured by [date]	100%					
		All permits and approvals completed by [date]	100%					
		Construction completed and project fully commissioned by [date]	100%					
Performance	Annual service quantity is achieved	Annual total of CO_2 captured and stored	[value]					
	Life cycle analysis is conducted annually	Service quantity determined by standard methodologies, protocols, or equipment (as applicable)	yes					
		CO_2 emissions caused by delivering annual service quantity	[value]					
		Life cycle analysis provided on an annual basis	yes					
	Storage is achieved	Storage term achieved	[value]					
		Monitoring and verification systems implemented to monitor storage	yes					
		Certification protocol developed (if applicable)	yes					
	Cost reduces over time	Capital expenditures per tonne	$/tonne					
		Operating expenditures per tonne	$/tonne					
		Monitoring costs per tonne	$/tonne					
		Storage costs per tonne	$/tonne					
	Scalability is demonstrated	Tonnage captured and stored annually	[value]					
		Projected time to scale	[value]					
		Number of individual buyers	[value]					
		Number of buyers purchasing > 1,000 tonnes	[value]					
Collaboration	Open communication and information sharing	Regular updates provided on progress, obstacles, and business development	yes					
		Carbon return/reversal events (voluntary and involuntary) communicated and compensated, as appropriate	yes					

Shopify Carbon Removal Playbook – Link

XPRIZE will evaluate the MRV standards of Phase 2 projects with a new Rules document

General description	
Description and classification	• **Classification**: The Competition Rules & Guidelines provide high-level rules and requirements for XPRIZE Carbon Removal, including the testing criteria. • **Background**: XPRIZE is a non-profit organisation which hosts funding competitions for projects which benefit humanity. In 2021, the organisation launched the £100m Carbon Removal competition in order to help scale efficient solutions to collectively achieve the 10 Gt per year carbon removal target by 2050. The competition allocates prizes of varying sizes ($50m, $30m, $15m, etc) to projects which can demonstrate GGR solutions which are low cost and scalable to Gt per year capacity. Phase 1 (proof of concept) ran from 2021-2022, and Phase 2 (demonstration) runs from 2022-2024. Detailed MRV requirements were outlined in the Phase 2 guidance. • **Governance**: To win the prize teams must demonstrate CO2 removal at the kt/y scale, model costs at the Mt/y scale, and present a plan to reach Gt/y scale.
GGR relevance	• The competition covers both nature-based and engineered solutions, with eligible engineered GGRs being DACCS, OAE, DOR, enhanced weathering and mineralisation.

MRV and accounting basics (based on the Phase 2 guidelines)	• **Scale:** the minimum scale of each project must be at least 1 ktCO2/yr (with credible pathway to Mt/yr and Gt/yr scale in the future).
	• **Durability:** The formula for "net removals" is calculated to be $Removed_{net} = Removed_{gross} \times (1 - Reemission_{100}) - Emission$. Captured emissions are expected to be removed for a minimum of 100 years (measured on a flux of 1000 years), and therefore the $Reemission_{100}$ factor deducts the proportion of CO2 which is not expected to meet this standard. Durability can be proven either via a known 100+ year storage route (i.e. calcium carbonate) or with active or passive management of a <100 year storage route which results in a net CO2 drawdown of 100+ years.
	• **MRV**: Finalist Teams must participate in XPRIZE's Measurement & Verification (MRV) process in order to be considered for a grand prize. MRV is completed by 3rd party contractors hired and paid for by XPRIZE during the verification period indicated in the competition schedule. In addition to a cost analysis, MRV consists of:
	  • **Performance verification:** applicants are directed to draw a MRV plan from ISO14034 (2016), Hansen et al (2021)[1], the Gold Standard (2022) and Microsoft standard (2021), with minimum verification activities involving an on-site technical audit, regular data reporting from the CDR demonstration team, sample collection and analysis, independent sensors or remote data acquisition, and a review of performance data.
	  • **Sustainability analysis:** applicants are directed to draw from several methodologies including LCAs, impact assessments, GHG accounting, environmental justice and approaches outlined in Langhorst et al (2022)[2], ISO 14040 (2020), ISO 14044 (2020), European Commission[3], and Skone et al (2022)[4]. Necessary information includes (but not limited to) functional unit/reference flow of one metric tonne of CO2 removed from the atmosphere/ocean and durably sequestered, cradle-to-grave LCA, mitigations plans, quantification of uncertainty ranges for all applicable indicators, and assessment of sensitivity.

Crediting	N/A – projects are competing for lump sum grants and are not issuing credits through the XPRIZE competition
Key documents	• XPRIZE Carbon Removal guidance – Link • XPRIZE Carbon Removal Phase 1 guidelines – Link • XPRIZE Carbon Removal Phase 2 guidelines – Link

[1] – Integrating the ISO 14034 standard as a platform for carbon capture and utilization technology performance evaluation. [Link]

[2] – Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO2 Utilization (Version 2.0). [Link]

[3] – International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment -Detailed guidance

[4] – Carbon Dioxide Utilization Life Cycle Analysis Guidance for the U.S. DOE Office of Fossil Energy and Carbon Management Version 2.0

BeZero provides ratings to various GGR credits based on a risk matrix comprising of several factors

General description	
Description and classification	• **Classification**: The BeZero Carbon Sector Classification system is a hierarchical sector classification system for the Voluntary Carbon Market (VCM). • **Background**: The BeZero Carbon Rating provides users with a risk-based assessment for understanding and interrogating carbon credit performance of any type, in any sector and country. **This includes rating projects which have been accredited by schemes listed in this report (Verra, Gold Standard, American Carbon Registry, etc).** Non-public information is not considered. The BeZero Carbon Rating (BCR) of voluntary carbon credits represents BeZero Carbon's current opinion on the likelihood that a given credit achieves a tonne of CO2e avoided or removed. • **Governance**: The BCR is conveyed using an eight-point alphabetic scale ranging from 'highest' to 'lowest' likelihood. This ranges from AAA (highest likelihood of achieving 1 tonne of CO2e avoidance or removal), AA, A, BBB, BB, C, and D (lowest likelihood of achieving 1 tonne of CO2e avoidance or removal). The rating process works in a through a four step process – Stage 1: macro factor assessment; Stage 2: project specific assessment; Stage 3: risk factor weighting; Stage 4: BCR committee review.
GGR relevance	• The relevant engineered GGR sectors rated by the BeZero system are labeled as "Tech Solutions" (Sector Group 5) and consist of biochar, building materials (brick manufacturing and wooden building materials), CCS (BECCS, DAC, EOR), and enhanced weathering.
MRV and accounting basics	• The BeZero Carbon Rating follows an analytical framework involving detailed assessment of six critical risk factors affecting the quality of credits issued by the project, each ranging from significant risk, notable risk, some risk, little risk, and very low risk. • **Additionality**: The risk that a credit purchased and retired does not lead to a tonne of CO2e being avoided or sequestered that would not have otherwise happened. Significant risk means that projects face significant risks of non-additionality because few barriers exist, and very low risk means that the sole purpose for such projects is carbon removal or reduction and without carbon finance, projects are entirely unviable. • **Over-Crediting:** The risk that more credits than tonnes of CO2e achieved are issued by a given project due to factors such as unrealistic baseline assumptions. Significant risk means that inflated baselines or significant over-crediting risks exist and very low risk means that very low over-crediting risk is present. • **Leakage**: The risk that emissions avoided or removed by a project are pushed outside the project boundary. • **Non-permanence:** The risk that the carbon avoided or removed by the project will not remain so for the time committed and any associated information risk. • **Policy:** The risk that the policy environment undermines the project's carbon effectiveness. Significant risk means that the policy environment is highly supportive (e.g. measures are already legislated for, thereby undermining the project's carbon effectiveness), while very low risk means that there is very low policy risk to carbon effectiveness (i.e., the project demonstrates success in the face of an unsupportive policy environment). • **Perverse incentives:** The risk that benefits from a project, such as offset revenues, incentivise behaviour that reduces the effectiveness.
Key documents	• BeZero website – Link • BeZero Carbon Rating (March 2023) – Link

Task 5 assessed the suitability and deliverability of existing MRV methodologies and standards for use by the UK Government in GGR policy

Objectives

- Assess the suitability of standards for potential UK Government endorsement or adoption for each GGR technology.
- Discuss the potential implications of adopting or endorsing third party standards.
- Identify and explore how a UK GGR MRV standard might interact with existing UK standards, policies and regulations.
- Evaluate the pros and cons of different MRV implementation options.
- Provide overview of potential MRV adoption, development and/or implementation strategies over the short, medium and long-term for the UK Government.

The assessment criteria included:

Criteria	Definition
Suitability of methodologies	Suitability of methodologies to successfully address the key LCA and MRV considerations of GGR technologies. Assessed for each existing / proposed methodology based on Task 4 results.
Assurance	Level of assurance and reliability of reported GHG reductions from GGR activities, based on verification requirements.
Environmental and social safeguards	Inclusion of non-GHG sustainability and social safeguards, e.g., ecosystem/biodiversity, environmental services, land rights, water, working conditions, etc.
Credibility	Public perception, track record of grievance or negative comments from civil society organisation, governance (inclusiveness and transparency).
Governance	Existence of clear boundaries between the standard/methodology development process and MRV implementation mechanisms (verification and issuance of carbon credits). Independent scientific advisory and includes multi stakeholder feedback in methodology development.

Puro Earth

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	The methodology does not consider wider system impact of additional renewable energy demand. Although the methodology requires compliance with local CCS regulations, there are no explicitly stated minimum provisions relating to MRV around CO_2 storage, leak detection, liability transfer, etc.
BECCS	The methodology addresses biomass related considerations relatively well, however, the CO_2 storage related issued discussed in the DACCS section are also applicable here.
Biochar	There are still some concerns related to handling of indirect land use change and evidence of biochar application to site.
Enhanced Weathering	The standard provides many suggestions, but requirements are currently limited (understood to be due to nascent nature of ERW applications/techs).
Building Materials	The methodology misses emissions from distribution of certain types of end products. Furthermore, there are uncertainties around the requirements for measurement of captured CO_2, such as frequency and accuracy of testing.
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	Independent third-party verifiers must assess the eligibility of new projects during registration and issue an audit report. Annual Output Audits are required to verify the output reports of project developers, which are evaluated by the Issuing Body.
Env/Social Safeguards	All methodologies include a generic environmental and social safeguards clause requiring projects to demonstrate that they do no significant harm. Although some recent methodologies provide additional detail on what these entail, requirements are still more vague compared with some of the other standards.
Credibility	Puro Earth has no major reported concerns about its credibility. It only certifies durable GGRs and is not involved with activities that are deemed more controversial, such as avoided deforestation.
Governance	Puro is open to accepting new methodologies and the Advisory Board has the mandate to update the existing methodologies if they believe sufficient changes have happened. Any such recommended updates are published for public comments and Puro Earth responses. However, the details of how new methodologies are developed are not provided online. There is uncertainty around timelines, costs, and specific steps for methodology development.

Verra

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	No methodology
BECCS	No methodology
Biochar	Verra's biochar methodology is comprehensive. It specifies MRV measurement methods and frequency of measurement. One minor concern is that the methodology likely underestimates decomposition for locations with average soil temperatures above 20°C.
Enhanced Weathering	No methodology
Building Materials	The limited scope of energy and materials inputs, as well as the absence of any requirement to track long-term fate of building materials, means the current methodology for building materials is not adequate.
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	Verification is conducted by accredited third-party validation/verification bodies. Site visits are required for validation, as well as certain milestones, such as the first verification of the project after validation.
Env/Social Safeguards	Demonstration of contribution to at least three UN Sustainable Development Goals is required by the end of the first monitoring period and in each subsequent monitoring period. Feedstocks must meet additional sustainability criteria depending on the type.
Credibility	There has been some criticism levied at Verra-certified REDD projects (claiming they are consistently and substantively over-issuing carbon credits). Verra has publicly denied these claims*. However, there is no evidence of criticism for the GGR technologies analysed in this study.
Governance	To approve a new methodology a public stakeholder consultation is conducted, and an accredited validation/verification body (VVB) assesses the methodology. Verra reviews the methodology and VVB assessment report and determines if the methodology can be approved.

*Verra response to Last Week Tonight episode on carbon offsets – Link
Verra response to Guardian report on rainforest credits – Link

Gold Standard

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	No methodology
BECCS	The proposed methodology has only one minor concern that it only allows CO_2 transportation through pipelines. However, the methodology is very limited in the scope of allowed BECCS technologies (fermentation only) and needs to be expanded to more types of BECCS.
Biochar	No methodology
Enhanced Weathering	No methodology
Building Materials	The existing methodology has only one minor concern: wider system impacts of energy use for atmospheric CO_2 capture are not accounted for. However, the methodology is very limited in the scope of allowed activities (concrete aggregates only).
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	Regular verification by independent third parties is needed before issuance of any credits. Although verification intervals may be flexible, annual status reporting is required.
Env/Social Safeguards	All projects are required to go through a comprehensive safeguarding principles assessment procedure and contribute to at least two other SDGs besides climate impact. Biomass feedstocks are required to comply with local sustainability regulations (e.g., RED II) or meet the renewable biomass definition in CDM EB 23 Report Annex 18.
Credibility	There are several reports from NGOs criticising afforestation & reforestation long-term carbon storage benefits. However, there is no evidence of criticism for the GGR technologies analysed in this study.
Governance	Public stakeholder consultations are required for both new methodologies and registering new projects. Internal and external scientific advisors are involved with the methodology development process. Projects have term limits for working with specific VVBs.

American Carbon Registry

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	The proposed methodology is expected to have only one minor concern, which is lack of consideration of embedded emissions in renewable energy infrastructure.
BECCS	The proposed methodology for BECCS has several notable concerns over treatment of feedstocks, such as exclusion of field emissions and emissions from cultivation, transport and processing of biomass even for new built plants, which would not have these emissions in their baselines.
Biochar	No methodology
Enhanced Weathering	No methodology
Building Materials	No methodology
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	ACR projects must be validated through a Validation / Verification Body (VVB), which are independent third parties, meet requirements of ISO 14065:2013 and be accredited by a body which is a member of the International Accreditation Forum.
Env/Social Safeguards	ACR projects must disclose information related to environmental and social risk identification and mitigation across several categories, connect projects to UN Sustainable Development Goals, and follow a "do no harm" principle. Biomass sustainability requirements are largely in line with the RTFO list of allowed feedstocks in the UK.
Credibility	There are several reports from NGOs and academics criticising real benefits and additionality of afforestation, forest protection, and renewable energy activities. These concern are less likely to apply to the GGR technologies analysed in this study.
Governance	Methodology development or updates to existing methodologies require reviews by independent subject matter experts and are open public consultations. This process is separated from project validation and verification activities.

Climate Action Reserve (CAR)

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	No methodology
BECCS	No methodology
Biochar	While there are adequate provisions covering decomposition, co-products, counterfactual, indirect land use change, etc, there is a concern about the exclusion of emissions associated with fertiliser or pesticide use for primary biomass feedstocks.
Enhanced Weathering	No methodology
Building Materials	No methodology
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	CAR requires periodic third-party verification of all GHG projects and their documentation, monitoring data and procedures used to estimate GHG reductions or removals.
Env/Social Safeguards	CAR requires project developers to demonstrate that the projects do not undermine progress on other environmental issues (air and water quality, endangered species, natural resource protection, etc) and must comply with all applicable environmental laws and regulations. Some additional requirements may be included for individual protocols.
Credibility	CAR also credits forestry projects. There are several reports from NGOs and academics criticising real benefits and additionality of afforestation, forest protection, and renewable energy activities. These concern are less likely to apply to the GGR technologies analysed in this study.
Governance	The methodology adoption process requires stakeholder and public consultations. The methodology development progress and updates from CAR working groups are available online.

Carbon Standards International

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	No methodology
BECCS	No methodology
Biochar	While some provision categories are satisfactory (particularly those related to material inputs for feedstocks), there are minor concerns around accounting for indirect land use change impacts and the method for calculating biochar decomposition.
Enhanced Weathering	The standard for enhanced weathering is still being developed. The current lack of method for determining the counterfactual and quantification of baseline would make the standard (in its current state) inadequate for enhanced weathering projects.
Building Materials	No methodology
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	Certification is carried out by q.inspecta GmbH, an accredited certification body which is also part of the Easy-Cert group. There is no detailed procedure for other accrediting bodies other than q.inspecta.
Env/Social Safeguards	There is a full set of environmental/social criteria. Projects must meet all local and national regulations on environmental protection and health and work safety, and all relevant national and European regulations on fertilisation and soil protection. However, there is limited provision over the impacts of indirect land use change.
Credibility	No concern reported. EBC is also referenced by other standards (i.e., Puro Earth accepts EBC certification for biochar methodology).
Governance	Ithaka Institute (non-profit) developed both technology methodologies, with updates required every three years. A Scientific Advisory Committee, Technical Committee and (depending on the technology) external expert group all contribute development. An agreed pre-final version then progresses to a public consultation.

Climeworks & Carbfix

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	The Climeworks / Carbfix methodology currently only cover solid-sorbent capture (<120°C) and storage via rapid mineralisation or supercritical injection. Both storage techniques are currently at a lower TRL and expected to be less common than more conventional stratigraphic trapping practices. No consideration is included for the wider energy system impacts of substantial electricity demand. The methodologies would also need complementary requirements for CO_2 transport from another methodology.
BECCS	No methodology
Biochar	No methodology
Enhanced Weathering	No methodology
Building Materials	No methodology
Ocean GGR	No methodology

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	As a stand-alone methodology there is limited explicit requirements for independent third-party verification, although DNV certifies all of Climeworks' credits from the Orca plant before issuance to clients. Still, there is only one VVB involved for both methodology validation and project verification.
Env/Social Safeguards	The methodology requires projects to do no net environmental or social harm and comply with applicable local environmental, ecological, and social statutory requirements. However, there are no quantifiable or measurable requirements, especially with regards to the large volumes of water required.
Credibility	The methodology has been implemented in a pilot scale DACCS project in Iceland and will be used in the upcoming scale up projects. While there is a large volume of R&D publications from Carbfix, the DACCS methodology does not yet have long-standing commercial-scale credibility.
Governance	The methodology was audited and validated by an independent verifier and Carbfix collaborated with iCert to ensure compliance with ISO 14064-2. However, there was no public consultation. Methodology validation against ISO standards and verification of project activities were conducted by the same organization.

Planetary

Assessment of treatment of GGR technologies (Suitability)

Tech	Assessment
DACCS	No methodology
BECCS	No methodology
Biochar	No methodology
Enhanced Weathering	No methodology
Building Materials	No methodology
Ocean GGR	The Planetary standard (V2) provides a sufficient instruction to analyse air-sea gas exchange and recognises the significant uncertainty in OAE projects (mitigated in part by credit discounts). However, the standard will require further developments to effectively govern and verify secondary chemical impacts of OAE projects*. The standard also does not cover DOR or electrochemical OAE projects (due to the initial standard only being developed for mineral OAE), making the current standard (V2) inadequate for all ocean GGRs.

Assessment of general characteristics of the standard

Criteria	Assessment
Assurance	Verification is required to be performed by an independent third party, however, specific criteria for VVBs are not listed, nor is info on how their output reports will be audited to avoid conflicts of interest.
Env/Social Safeguards	Other than emissions associated with LCA, the standard does not contain any additional sustainability requirements (it only states the benefits of Planetary's chosen mineral). While the standard does state that the Planetary team is dedicated to ensuring that ecological risks are minimised, there is currently no quantifiable requirement for assessment of these risks on regular monitoring intervals.
Credibility	Planetary hosts a GitHub repository where MRV queries can be asked and answered. However, the methodology lacks a strong track record due to its current immaturity. This may grow increase with time with the proposed pilot project.
Governance	Planetary hosts a "live" consultation where the company answers questions from registered users on the website. However, it remains unclear to what extent Planetary must submit to external governance (expert review, etc).

*It is recognised that direct quantification of these impacts may be challenging, and the development of ocean GGR standards may be somewhat rate-limited by the development of sufficient oceanographic models

The review of existing MRV methodologies and standards revealed that in their current state, none would be appropriate alone to cover all the engineered GGR technologies in scope

Are any of the methodologies suitable for any GGR technologies?

- **Few existing MRV methodologies** were deemed suitable for possible UK Government endorsement **in their current form** (before UK-specific policies are overlaid).
  - This reflects the developing nature of many of the GGR technologies reviewed, as standard practices and best available MRV techniques are still being determined.
  - The only methodologies which could be endorsed without significant revisions or expansions are Verra's biochar and the American Carbon Registry's DACCS methodologies.
  - Two other methodologies – Gold Standard methodologies for BECCS fermentation and carbonation of concrete aggregates – were found to be suitable for certifying their respective GGRs. However, these are currently restricted in scope and would require significant expansion to cover a larger number of GGR technologies.
- However, some of the methodologies rate **more favourably** and may be suitable for adoption by the UK Government if **existing UK standards and policies** (e.g., in CCS and biomass) are considered alongside the current GGR standards. These are Puro Earth's methodologies for DACCS, BECCS and biochar, Climeworks / Carbfix methodology for DACCS and Carbon Standards International methodology for biochar.
- Companies which have developed their own MRV methodologies for **specific projects** (Planetary, Climeworks / Carbfix, etc) provide a useful platform to further support the deployment of MRV schemes. However, these methodologies **lack the scope** required to become a governing standard, as they often only deal with a specific configuration within a GGR technology.
- **Other standards** (Microsoft, Shopify, XPRIZE, etc) provide useful overviews of additional MRV considerations for individual GGR technologies and projects. However, endorsing or adopting these as an MRV standard **would be challenging**, as many are merely assessment criteria for credit purchases rather than true MRV standards.
- **The standards sector for GGR MRVs is evolving rapidly,** with multiple new methodologies and updates published while this study was conducted. As a result, the conclusions in this report are subject to market evolution and may need to be revisited in the future.

Several existing UK policies are applicable to different GGR technologies, which can be incorporated into MRV methodologies to reduce overall risks

How could other existing aspects of UK policy interact with, support, or alter how GGR MRV frameworks are assessed?

- The UK has several existing standards and policies which affect various components of the GGR value chains. The combined requirements of these policies/standards with an MRV methodology could give an adequate MRV approach.
  - The UK has a mature CO_2 geological storage licensing and regulatory regime through **the storage of Carbon Dioxide (Licensing etc.) Regulations 2010**. These have the potential to be integrated into a variety of MRV standards for projects involving geological CO_2 storage (i.e., DACCS, BECCS and ocean DOR), and potentially enhances MRV credibility.
  - The UK already has **biomass sustainability requirements under various government support schemes** – such as the Renewable Transport Fuel Obligation (RTFO) for renewable transport fuels and Renewables Obligation and Contracts for Difference for power generation. These have the potential to be integrated in a variety of MRV standards for UK projects utilising biomass as a feedstock (e.g., BECCS and biochar).
  - The **Low Carbon Hydrogen Standard (LCHS)** could provide a threshold for carbon intensity in hydrogen produced via BECCS processes.
  - **The Environmental Targets (Marine Protected Areas) Regulations 2022** mandates that at least 70% of protected features in MPAs to be in favourable conditions by 2043, with the remaining features to be in a recovering condition. This could affect the location and allowable activities for ocean GGR projects, which could be seen to either support or detract from these targets, depending on assessment of secondary impacts.

There are additional factors to consider which may affect the suitability of existing MRV standards for adoption by the UK Government

If the UK Government decides to work with existing standards, which are some additional factors affecting suitability?

- **Credibility** of many of the GHG methodologies was identified as a possible issue.
  - This was recognised as primarily due to both a lack of track record in the engineered GGR sector and association with nature-based emissions reduction / avoidance activities (which have been subject to recent scrutiny by some NGOs and news organisations).
  - However, schemes which are specifically dedicated to engineered GGRs (e.g., Puro Earth, EU CRCF, and Carbon Standards International) may avoid this credibility challenge and see their credibility grow with time spent actively developing and assessing projects.
- **Quality** of GHG and MRV methodologies will be continuously improved through regular updates
  - The first methodologies developed for a technology may not address all key considerations identified in this study. This could be due to the long time periods needed to clarify certain methodological aspects and the benefit of continuous improvements through trial and error. For example, for some of Puro Earth's early methodologies (e.g., DACCS/BECCS and enhanced weathering) quality considerably improved with updates (e.g., carbonated materials methodology update in June 2023) and Puro Earth is actively working on further updates.
- Methodologies involving **GGR technologies at lower technology readiness levels** (e.g., ERW and ocean removals) will require more time to achieve the expected level of quality and robustness.
  - This reflects the immature development status of these technologies, with MRV standards expected to improve through further demonstration projects.
  - Advancements may take place over a period of 5-10 years due to current significant scientific uncertainty, challenges with monitoring an open system vs a closed system and expected additional reliance on modelling over direct measurements.

There are several options for the UK Government to establish GGR MRV requirements

What are the options for the UK Government to implement an MRV standard?

1. **Endorsement of a single standard**
   - UK Government could endorse a single existing standard, depending on its coverage of GGR technologies and the quality of methodologies. Under this option the government would have limited to no influence over the methodologies, including any future changes.

2. **Endorsement of multiple standards for different technologies**
   - Instead of one standard, UK Government could endorse multiple methodologies (potentially within different standards) for different GGR technologies.

3. **Bilateral partnership with one or more standards to develop joint methodologies**
   - UK Government could work with a standard(s) provider to expand / update its current coverage of methodologies. This may be done through the methodology development processes most standards employ (i.e., the government submits methodology applications as a third party) or through a bilateral partnership (i.e., UK Government and the standard actively work together on methodologies).

4. **Development of a new, independent GGR MRV standard**
   - UK Government could develop and administer its own GGR standard and methodologies independent of existing carbon certification schemes. Alternatively, the government could still develop its own GGR methodologies, but partner with third party standards for administration of the scheme (i.e., California and Washington cap-and-trade systems) to leverage existing infrastructure of these standards.

5. **Setting minimum criteria, then allowing project developers to follow any MRV methodology**
   - UK Government could develop a set of minimum quality requirements for GGR certification methodologies depending on national interests and international best practices. All project developers may then submit their MRV plans for approval under these requirements. Projects may seek certification under existing standards or develop their own methodologies (i.e., the approach taken by the Frontier Fund – see overview of Frontier under “other standards” in section T3&4).

Each of the five identified options for MRV development have accompanying advantages and drawbacks which would need to be carefully considered

1 Endorsement of a single standard

Pros
- Relatively administratively simple
- Leverages existing experience and knowledge of private standards, including the validation and verification bodies (VVBs) that carry out assessments

Cons
- No suitable standard to certify all GGR technologies in scope
- Over-reliance on one standard, which may change in scope and provisions
- Higher credibility risk exposure from a single partner

2 Endorsement of multiple standards

Pros
- Relatively administratively simple
- Leverages existing experience and knowledge of private standards, including VVBs that carry out assessments
- Combines the most suitable methodologies from different sectors

Cons
- May be confusing for some stakeholders
- Limited / no influence over how methodologies may change in the future
- Credibility risk is more spread, but still present

3 Partnership with standard(s) to develop joint methodologies

Pros
- Larger flexibility with tailoring methodologies
- Leverages existing experience and knowledge of private standards, including VVBs that carry out assessments

Cons
- HMG may need to provide financial contributions to the standards for expansion of methodologies
- More administratively complex than direct endorsements
- May lead to standards / methodologies inflation in the GGR sector (minor)

4 Development of an independent new GGR MRV standard

Pros
- Can be tailored for UK Government's requirements and context
- Likely to carry high credibility since it will be a public scheme, although some risk exists if external standards are used for administration.
- May be inspired by best examples from other standards
- No need to make financial contributions to third parties if the UK Government takes on the administration task

Cons
- Administratively complex – likely requires significant scientific and stakeholder input, which can be time consuming
- May lead to standards / methodologies inflation in the GGR sector (minor)
- VVBs would need to be trained to get familiar with the scheme, especially if the UK Government takes on the administration task

5 Allowing any MRV methodology that satisfies minimum criteria

Pros
- Additional flexibility to accommodate less mature GGR technologies
- Allows government to take most appropriate practices from a variety of methodologies, without having to transpose the entire standard
- Can be implemented relatively quickly for early projects
- Presents a consistent framework for consideration of different MRV standards, although individual GGR projects would still be treated slightly differently as they can follow different standards.

Cons
- Can be administratively burdensome, especially in the long term, since each MRV standard submitted would have to be assessed.
- May lead to standards / methodologies inflation in the GGR sector (minor)

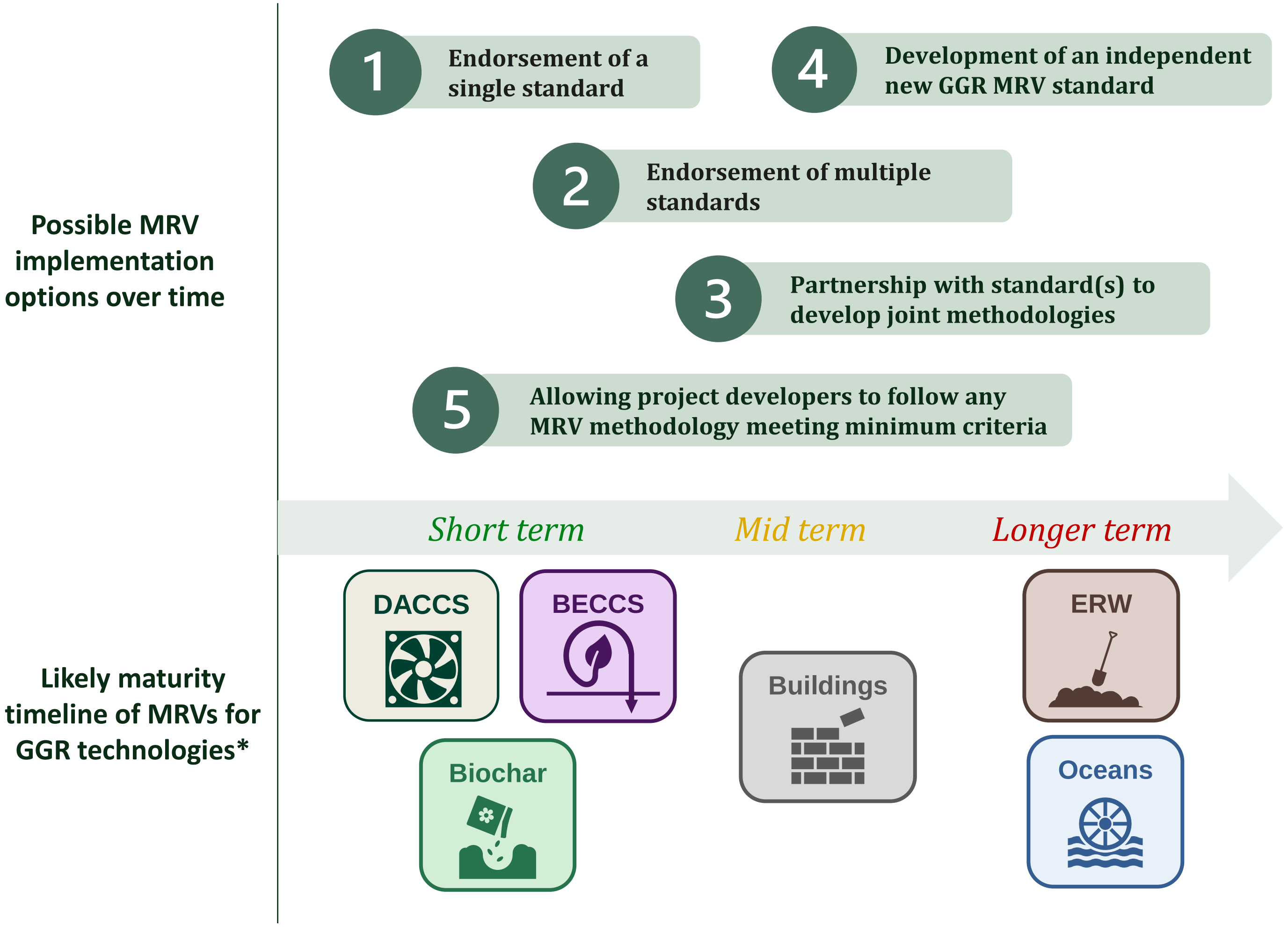
Some MRV options can be implemented faster than others and allow for a transition between options, matching future development of GGR technologies

Different MRV development options could be implemented based on the priorities and capabilities of the UK Government and technical maturity of different GGRs.

- Endorsing one or more standards (options 1 and 2) or developing minimum criteria (option 5) could be done in the shorter term, with a possible transition to an independent standard (option 4) in the long-term.

This also gives the UK Government flexibility when engaging with GGR technologies at different maturity levels.

- Developing a new methodology for less commercially-ready technologies (ocean GGRs and ERW) would be more challenging, meaning setting minimum criteria (option 5) might be necessary to give greater flexibility as experience develops.
- This may contrast with more commercially-ready technologies (such as DACCS and BECCS), where it would be more feasible to develop or endorse more detailed methodologies earlier.



* Note that this timeline only includes the six engineered GGRs focused on in this study, however, MRV frameworks for other engineered GGRs (e.g., biomass burial, bio-oil injection, etc.) could also be developed.

Thank you

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