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Measurement, reporting and verification (MRV) and accounting for carbon dioxide removal (CDR) in the context of both project-based approaches and national greenhouse gas inventories (NGHGI)

Technical Report 2024-09
October 2024

IEAGHG

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To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

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MEASUREMENT, REPORTING AND VERIFICATION (MRV) AND ACCOUNTING FOR CARBON DIOXIDE REMOVAL (CDR) IN THE CONTEXT OF BOTH PROJECT-BASED APPROACHES AND NATIONAL GREENHOUSE GAS INVENTORIES (NGHGI)

(IEA/CON/22/289)

The aim of this study is to provide a synthesised technical assessment of carbon dioxide removal (CDR) methods and review their measurement, reporting, and verification (MRV) features and accounting aspects.

Note: We are providing the usual IEAGHG Overview for this study, however we highly encourage interested readers to read the full report, as the topic is complex and highly contextual and any attempt of summarising it will necessarily lead to a loss in detail and context.

Key Messages

- Reasons persist for being both positive and circumspect about the role of CDR in climate action. On the one hand, CDR seems essential for achieving the Paris Agreement. On the other hand, CDR poses significant challenges for climate policy.
- A number of MRV efforts are underway today by private and public actors in both the voluntary carbon markets (VCM) and compliance (regulated) carbon markets. The discussions and outcomes from these processes will have clear ramifications for the way in which MRV approaches and methodologies will be used to calculate and verify CDR actions in future. Yet, at time of writing, much debate and uncertainty remain regarding the best means of doing so.
- The technical review of CDR methods highlights that questions remain over the foundational science (except relating to engineered geological storage and biological capture and storage) and/or social acceptance underpinning most CDR methods. As such, the view that a portfolio of CDR methods is likely to be needed to meet the Paris Agreement is reaffirmed.
- For CDR methods such as soil organic carbon (SOC), enhanced weathering (EW) and ocean-based CDR, challenges persist for monitoring CO_2 flux rates, carbon (C) stock changes and the fate and behaviour of C carriers in the environment. Despite indications that a CO_2 drawdown effect can be expected, monitoring of field trials have in many cases been unable to corroborate these hypotheses.
- Recent focus has been almost exclusively on developing project-based methodologies, which are inherently consequential and rely on baseline scenarios and counterfactuals that are notoriously difficult to establish. Thus, related additionality testing in credit schemes has been subject to widespread criticism.
- Two critical issues for the current approach to CDR crediting/certification exist:
    1) Policy utility: If certified/credited CDR activities do not create a symmetrical[1] and equivalent amount of CDR in the host country national greenhouse gas inventory (NGHGI) – a problem that can be termed 'inventory visibility' – then any policy designed to incentivise CDR will lack political utility.

[1] Significant asymmetries can arise between what is 'MRV'ed', certified and credited at a project level and whether and how the same action may be recorded a host country's NGHGI.

2) Long-term responsibility: Host countries are ultimately the 'underwriter of last resort' for carbon reversal, i.e. they will need to take very long term responsibility for the carbon storage and manage the risk of carbon reversal. Better understanding of the liability of any carbon reversals may impair countries' willingness to host CDR activities, a problem that can be further exacerbated by inventory visibility.

- Ocean-based CDR methods pose unique challenges in these regards: since the C reservoir falls outside of national MRV frameworks, any CO_2 drawdown will be neither visible in any country's NGHGI nor subject to any host country monitoring that could offer to accept liability for carbon reversal. Until these challenges are addressed, ocean-based CDR will not meet UNFCCC accounting standards.

Background to the Study

The subtle shift in emphasis away from a focus on reducing and eliminating GHG emissions (as in the quantified emission limitation and reduction targets of the Kyoto Protocol) towards net zero framing has shone a new light on the role and potential of GHG removal (GGR) or CDR in climate change mitigation[2]. Today, there is growing acceptance that CDR methods are needed to offset some ongoing, hard-to-abate, residual anthropogenic GHG emission sources to achieve and thereafter maintain a state of net zero (IPCC 2022).

The topic of CDR is, however, not new to climate policy discourse. Experiences with the governance and accounting of emissions and removals arising from land use, land use change and forestry (LULUCF) and the enhancement of geological reservoirs using carbon capture and storage (CCS) were an important and contentious feature of the Kyoto Protocol negotiations (e.g. Höhne et al. 2007; Dixon et al. 2013; Dooley and Gupta 2017).[3] These experiences provide value lessons that can be drawn upon to inform today's policy approaches. The net zero framing has rather provided CDR with a renewed momentum, building upon both the longstanding need to better manage terrestrial C stocks through conservation and enhancement, and for other, novel, methods of human induced CDR that can enhance a range of planetary C sinks and reservoirs.

The changing emphasis around CDR is clear in today's climate change policy discourse. Since the entry into operation of the Paris Agreement in 2020 there has been a steady expansion of the voluntary carbon market (VCM; e.g. drawing form the Taskforce for Scaling Voluntary Carbon Markets; TSVCM 2021) and therein a growing recognition that offsetting of emissions using credits originated from emission reduction or emissions avoidance activities alone will not deliver a 'net' zero outcome (e.g. Allen et al. 2020; Smith 2020).

In the voluntary carbon market (VCM), developers of project activities that reduce or remove emissions can apply to registries for the issuance of carbon credits (e.g. UNFCCC clean development mechanism, Verra/VCS, Gold Standard, ACR, Puro.earth etc). The methodologies for certifying and crediting these actions are established by the registries, covering various measurement, reporting and verification (MRV) requirements and usually taking account of the full chain of emissions and removals of these

[2] Hereafter the term 'CDR' is used in this report and focuses only on CO_2 removal methods, i.e. the methods must capture CO_2 from the atmosphere (either directly from the air or via biomass). Conventional fossil-based CCUS is not considered. CDR methods can have widely ranging carbon storage times.
[3] See also: https://unfccc.int/topics/land-use/workstreams/lulucf-under-the-kyoto-protocol/reporting-and-accounting-of-lulucf-activities-under-the-protocol

project activities relative to a counterfactual, baseline, scenario. Once an activity is approved and registered, and ongoing MRV shows reductions or removals, credits may be issued to the developer. The credits can be voluntarily acquired and cancelled by entities to be counted against their own reported GHG emissions.

In the past three years, an increasing number of CDR concepts, reports, platforms, and, increasingly and importantly, policy actions, are focussed on specifically addressing and/or promoting CDR.

In 2022, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), in its 6th Assessment Report (AR6; IPCC 2022), dedicated significant new text to the cross-cutting topic of CDR (Babiker et al. 2022).

Today, many research groups are scrambling to integrate a wider range of novel CDR methods into the integrated assessment models (IAMs) that are used to inform climate action decision-making. CDR-specific policy is also evolving, including at international (UNFCCC) and national levels (in particular in the U.S., the European Union (EU), Sweden, Denmark, Switzerland and the UK among others).

Nevertheless, while there is clear momentum in the CDR space, a number of challenges persist. One such issue receiving particular attention is the need for robust quantification methodologies and effective MRV approaches that can accurately determine the net amounts of C/CO_2 removed by various human-induced CDR activities. Assurance over the efficacy, efficiency, safety and ongoing durability of C stored in enhanced sinks and reservoirs is essential to build confidence in CDR methods and to foster further development.

A number of MRV efforts are underway today by private and public actors in both the VCM and regulated carbon market. The discussions and outcomes from these processes will have clear ramifications for the way in which MRV approaches and methodologies will be used to calculate and verify CDR actions in future. Yet, at time of writing, much debate and uncertainty remain regarding the best means of doing so.

Scope of Work

IEAGHG commissioned Carbon Counts, UK, to consider some of the specific MRV and GHG accounting aspects relating to CDR. This includes the following tasks:

1. Provide a high-level summary outlook for CDR, drawing upon recent literature;
2. Provide a synthesised technical characterisation and assessment of CDR methods;
3. Review MRV features and accounting aspects of the assessed CDR methods and provide a broad evaluation of their 'MRV-ability';
4. Provide conclusions and recommendations for further work.

Findings of the Study

Characterising and assessing CDR methods

The following section provides a characterisation and high-level assessment of the key features of various CDR methods, and how these may impact upon their potential to meaningfully contribute towards climate change mitigation. In the context of latter, that is: to be deployed at a pace and scale broadly aligned with the Paris Agreement global net zero goal in the second half of this century.

The primary purpose is to offer indicative signposts as to the main opportunities and more challenging areas facing the deployment and scale-up of a range of CDR methods. The evaluation methodology is applied in three steps: clustering, criteria development, and evaluation.

Step 1 – Clustering of CDR methods

The first stage of the evaluation was to condense the number of CDR methods reviewed into a smaller set through clustering and categorization. The process reduces the results into a manageable set of findings that can assist in communicating the broad characteristics of CDR and the different choices and trade-offs they may present. Four broad categories of CDR methods are identified, primarily clustered according to similarities in the C storage medium (see Figure 1).

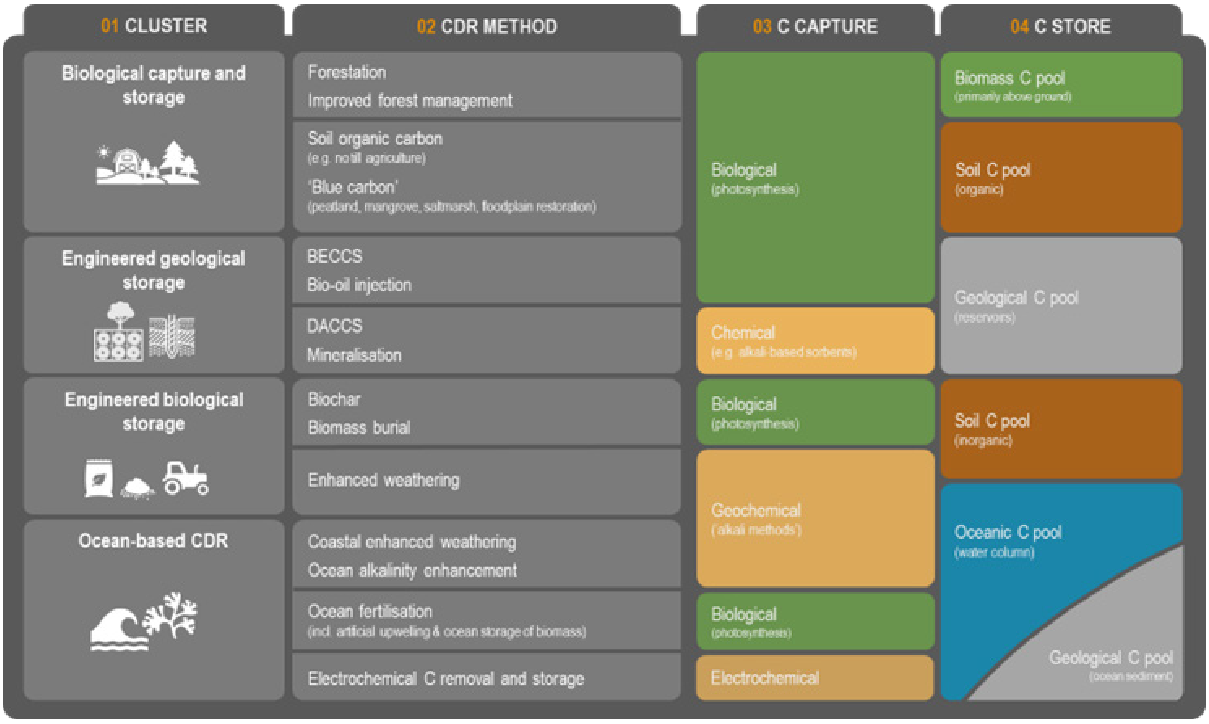

Figure 1 Taxonomic relationships used to cluster CDR methods

Clustering and categorisation based on the main C storage medium is not perfect, with several methods involving overlaps. There are other notable limitations in the taxonomic categorisation. For example, known combinations of C capture and storage not covered in the assessment include biomass burial in salt caverns, biomass sinking in lacustrine sediments, and biogenic C storage in the technosphere, the latter due to the challenges of defining acceptable levels of durability.

Step 2 – Evaluation criteria

The assessment here does not take into account the 'MRV-ability', as this aspect is covered more comprehensively later. While there are clear constraints in trying to take a broad view on all the evaluation factors described below in Table 1, useful signposts for policy trade-offs can be drawn from a fairly high level assessment, as outlined in the next section.

Table 1 Evaluation criteria applied to CDR clusters

Criterion	Description	Contexts
01 **Efficacy**	Proven capacity to remove C from the atmosphere (including at a rate useful to meeting near-term climate mitigation goals i.e. to 2050 or shortly thereafter)	Relates to the current level of understanding of basic, foundational, science. Inferred from the extent to which the method has been demonstrated in a working prototype or at field-scale (e.g. TRL 6 or higher), with field experiments showing discernible, measurable, CDR effects.
02 **Efficiency**	Ability to remove more C than is emitted (e.g. extent of unabated fossil energy consumption needed to deliver the removal effect).	Relates primarily to the full chain, lifecycle GHG emissions of the given CDR method. For many CDR methods, this is intimately linked the materials and energy used and the availability of decarbonised energy supply. Challenging to gauge, but at present can be considered to be finite and non-abundant. Also poses a paradox and significant questions over trade-offs: increasing the availability of decarbonised energy can reduce the need for CDR to achieve climate goals. The balancing point in these respects is presently unclear. Current IAMs heavily rely on BECCS, which delivers both decarbonised energy and CDR. As noted above, IAMs are seemingly not at a stage where they can fully address this paradox (Section 2.4).
03 **Durability**	Ability to store C for a length of time that is meaningful in respect of climate mitigation.	Relates to how long C can and should be stored for in the receiving media. Open discussions remain about what should constitute high durability (permanent) CDR. Present views on the matter are considered in the context of methodologies and MRV below (Section 4.2.5). Information presented there is used to inform the evaluation.
04 **Sustainability**	Ability to remove carbon with no or limited negative impacts upon the environment and society.	Relates to factors such as the abundance of, and impacts relating to, the sourcing and processing of input materials, energy, water etc. (e.g. source of biomass, source of clean energy, sufficient water availability, acceptable air emissions). Also, the amount of waste and wastewater production, including hazardous waste. Challenging to gauge. Most CDR methods pose the risk of some negative environmental and/or social risks and side effects, leading to trade-offs. Co-benefits can also be a feature (e.g. soil fertility, soil amelioration, biodiversity)
05 **Scalability**	Ability for deployment to expand to levels anticipated to be needed to meet near-term climate goals (e.g. to 2050).	Relates to availability and accessibility of relevant C storage media and of input materials needed in the CDR process (excluding socio-economic factors, per below) Challenging to gauge. Around 0.5 to 1.0 Gt by 2050 would seem like a meaningful threshold for scalability of a given cluster.
06 **Availability / Timeliness**	Ability to be deployed at scale in a relevant timeframe, taking account of other non-technical factors.	Societal and economic concerns could impede deployment and scale-up (e.g. cost, social license, legal impediments and barriers). These factors will reduce the rate at which the CDR might become available for it to upscale.

Step 3 – Characterising and evaluating CDR method clusters

The evaluation is informed by a review of literature, legal status and other sources undertaken by the authors, and application of their expert judgement in assessing the relevant advantages, trade-offs and barriers faced by each CDR cluster.

The findings for each criterion are gauged on a scale of approximately 1 to 10 (although no score is applied), and, unlike Fridahl et al. (2020), the framing of the criteria means that only positive attributes are applied (so a higher ranking means comparative benefits, and vice versa). The results are presented with notes against each criterion (see Table 2 - Table 5), and then displayed graphically using a spectrum analyser style 'light' gauge (see Figure 2 in the next section). The evaluation is not an attempt to identify the most promising methods and to "pick winners". As most observers and experts will contest, a portfolio approach to CDR is essential to address location-specific factors and mitigate against risks of failure (e.g. see Carbon Brief 2016). Thus, the aim is rather to attempt to characterise and relatively assess a broad range of CDR clusters so as to cast more light on the possibilities for certain CDR types to innovate and deploy in coming years relative to others.

Table 2 Evaluation summary of biological capture and storage

Criterion	Characteristics
Efficacy	Forests remove CO_2 from the atmosphere by converting it to woody biomass via photosynthesis. Efficacy of measures to enhance SOC are less certain; mixed results from field trials.
Efficiency	Tree planting is the main form of human induced terrestrial CDR. Few inputs needed, and certain agriculture practices to enhance SOC can reduce fertiliser and vehicle (tractor) use, leading to emission reductions. Rewetting of organic soils can reduce CO_2 fluxes from soil but increase CH_4 emissions in the short term (1-10 years). Can offset benefits of SOC enhancement (which can take longer)
Durability	Prone to human (deliberate) or natural (unintentional) rapid C reversal. Tree harvesting, changes in forest management, changes in agricultural practices, forest fires and pestilence all impact on the storage durability, can all rapidly deplete the C stock and release CO_2 (flux) to the atmosphere. Ploughing soil can rapidly deplete SOC stocks.
Sustainability	Depends on approach taken. High co-benefits of mixed native forest planting. Fertiliser use on marginal lands and planting of non-native monocultures will significantly impair environmental benefits (requires safeguards)
Scalability	Forestation: high (5-10 $GtCO_2e/yr$) SOC and blue carbon: moderate/uncertain (2-5 $GtCO_2e/yr$)
Availability / Timeliness	Forests and SOC need time (20+ years plus) to reach new levels of enhanced C stock. Low cost. Land competition will restrict availability of land available for forestation.

Table 3 Evaluation summary of engineered geological storage

Criterion	Features
Efficacy	CO_2 capture and storage is proven in a number of settings and applications worldwide. BECCS: several facilities in operation capturing biogenic CO_2 for geostorage DACCS: largest operational plant is 4000 tCO_2/yr Bio oil: number of small-scale projects in the U.S. injecting corn-derived bio-oil into depleted oil and gas wells.
Efficiency	Significant energy requirement (electricity to drive fans etc; heat for solvent regeneration) Embodied carbon in materials, water and energy use can significantly impair effectiveness and efficiency. Location specific.

Durability	For storage in well selected, designed and managed geological reservoirs the fraction retained is very likely to exceed 99% over 100 years (90-99% probability) and is likely (66-90% probability) to exceed 99% over 1,000 years (IPCC 2005)
Sustainability	Water and materials use can result in environmental impacts. Waste production (spent sorbents) can present an environmental burden. Co-removal of air pollutants can be a benefit.
Scalability	Technical potential is significant (>10 $GtCO_2$/yr) Availability of storage sites is not considered to be a significant constraint. Flexibility offered by DACCS could allow improved source-sink matching. Bio-oil injection likely to be limited by availability of oil and depleted wells in which to inject it.
Availability / Timeliness	Costs, public perception, project complexity, financing, permitting etc can all be expected to impact upon deployment rates (drawing from analogues from fossil CCS progress).

Table 4 Evaluation summary of engineered biological storage

Criterion	Features
Efficacy	Techniques are conceptually feasible. Biochar: assuming sustainable and uncontaminated feedstocks, production can lead to a C stock transfer from organic C pool (e.g. woody biomass) to the SIC (soil inorganic C) pool. EW: not yet proven in field trials. Biomass burial: leads to a C stock transfer to inorganic/organic soil C pool.
Efficiency	Biochar: may lead to negative priming in some circumstances (breakdown of in situ SOC). Evidence is mixed and conditions driving priming effects are difficult to discern. EW. Energy footprint of mineral acquisition, commutation and application can impact upon effectiveness and efficiency. Biomass burial: cost and energy needs of internment remain unclear but may be high relative to CDR effect achieved.
Durability	Biochar: IPCC (2019) indicative estimates of the 100-year retained fraction of 0.65-0.89, suggesting around 10 to 35% decay over 100 years. Experts estimate that, on average, 80% of biochar C persists in soil for >100 years (SLU 2023). EW: Conversion of bicarbonate to carbonate releases CO_2. In general terms, the characteristics of the soil inorganic carbon (SIC) pool is poorly understood, which hampers understanding of durability of these CDR methods. Biomass burial: natural analogues suggest potentially very long storage durations may be possible under specific conditions and circumstances.
Sustainability	Source materials (biomass quality, feedstock contaminants, mineral extraction) and processing (e.g. biochar conversion efficiency; biomass internment energy requirements) will significantly influence sustainability. Impacts on receiving environments remain largely untested (long term field trails yet to be concluded).
Scalability	Technical potential: moderate (~5+ $GtCO_2$/yr) Biomass burial: constrained by availability of sustainable biomass.
Availability / Timeliness	Biochar: requires scale up of significant new industry, and sufficient acceptance by farmers and other types of usage. Soil saturation levels may diminish potential. EW: yet to be proven at field scale. Biochar and biomass burial: constrained by availability of sustainable biomass.

Table 5 Evaluation summary of ocean-based CDR

Criterion	Features
Efficacy	Techniques are conceptually feasible. Field trials for some methods have been implemented, but results remain uncertain. Efficacy of biomass sinking yet to proven.
Efficiency	Energy footprint of mineral acquisition, commutation, processing and application can impact upon effectiveness and efficiency of most techniques. Biomass sinking methods yet to be optimised. Decay of sunk biomass could lead to CH_4 formation.
Durability	Uncertain. Conversion of bicarbonate to calcium carbonate (e.g. through synthesis by marine organisms) leads to release of CO_2 Ability of sunk biomass to deliver durable storage remains somewhat untested.
Sustainability	Source materials (biomass quality, mineral extraction), processing and application (e.g. energy use) significantly influence sustainability of various ocean-based CDR methods. Risks to marine ecology from e.g. liberation or mobilisation of nutritive or toxic elements; deoxygenation risk (from fertilisation) etc
Scalability	Technical potential: very significant (e.g. some estimates of OAE at 100 $GtCO_2$) Other estimates are generally more modest (5-15 $GtCO_2$)
Availability / Timeliness	All methods face barriers, especially legality under marine protection treaties.

Comparative assessment

The assessment indicates that CDR methods involving biological and geological storage are the most mature, with relatively higher levels of proven efficacy. Naturally-occurring biological CDR methods are the most efficient and sustainable, primarily because they do not require the input of significant amounts of energy or materials to increase C capture or to anthropogenically enhance terrestrial C sinks and reservoirs. Engineered biological systems also generally score well for efficiency and sustainability (however, sustainability issues for large-scale biomass applications apply), as they primarily rely on natural CO_2 capture processes. Geological CO_2 storage is seen to be the most durable in line with the geological C cycle (assuming short-term secure/stable storage in geological reservoirs). Uncertainty over long-term performance of biochar and EW reduces the assessed durability for these solutions. Some biological capture and storage and ocean-based CDR are considered to present the greatest risk of C reversal, in line with the potential for either natural and human induced events to rapidly deplete C stocks (e.g. forest fire, ocean circulation and upwelling).

Scalability and timeliness perhaps show the most interesting result. Most methods are considered to be scalable, consistent with estimated technical potentials. In respect of timeliness, all CDR methods face deployment challenges that hamper their ability to rapidly contribute towards climate mitigation by mid-century or shortly thereafter. In some cases, it is the timeframe over which the removal effect functions (e.g. tree growth), while for others, the need for decarbonised energy as well as other technical challenges can constrain deployment rates (e.g. CO_2 storage site identification, permitting and technology development). For ocean-based CDR, major legal and public perception impediments are likely to present ongoing obstacles to widespread deployment. Summary results of the technical evaluation are shown graphically below (see Figure 2). The results presented are for the clusters, thus it should be noted that single methods within each cluster might score better or worse than the average, and shading of the bars was used to highlight that there are associated uncertainties.

The generally lower scores and spread of scores shown across the final criterion of timeliness and availability reaffirms the widely held view that a portfolio of CDR will be essential to delivering meaningful climate mitigation over the near- to mid-term (see e.g. Carbon Brief 2016).

Figure 2 Summary results of CDR evaluation

MRV and accounting for CDR

Clustering CDR 'MRV-ability'

Based on the analysis and discussion presented in the report, a rapid assessment of CDR 'MRV-ability' has been undertaken. The evaluation was based around several key criteria as summarised below (see Table 6), which are described and discussed in more detail in the report.

Table 6 'MRV-ability' assessment elements

Element	**Criteria**
Boundaries & Leakage	▶ Can the CDR system boundary be readily defined? ▶ Is there clarity over how different emission sources and/or C pools should be treated? ▶ Are leakage risks identifiable and measurable?
Baselines & Additionality	▶ Can baselines be established and measured in a comprehensive manner? ▶ Is project additionality relevant and measurable? ▶ What is the risk of adverse selection or uneven additionality assessment?
Monitoring & Verification	▶ Can the capture and storage of CO_2 be directly observed and monitored? ▶ What levels of uncertainty can be achieved in monitoring the CDR effect? For which C pools? ▶ How significant is the CDR effect compared to other aspects impacting GHG effects (e.g. emissions avoidance)?
Permanence	▶ What is the risk of non-permanence of the removal effect? ▶ Can the risk of carbon reversal be managed to a tolerable level?

Accounting	▶ Is there a risk of double rewarding or double counting the GHG emission reductions/removals effect? ▶ Will the measured CDR effect at the activity level be integrated and aligned with NGHGIs?

The results from the evaluation are clustered around four categories:

- **Category 1 – Core, proven, CDR activities**. CDR methods falling within this MRV category can be readily integrated into climate policies, including associated trading and accounting frameworks. The focus here is engineered geological CO_2 storage solutions, especially BECCS and DACCS, drawing from the long-standing regulatory and accounting frameworks established for CCS, and the relative ease by which CO_2 fluxes can measured.

- **Category 2 – Known challenges**. CDR methods falling in this category face some known challenges, but could be integrated into climate policy, trading and accounting frameworks with some straightforward adjustments. These may include, for example, the boundary in respect of the scope of MRV requirements (e.g. in the case of forestation, focusing activity level MRV on aboveground biomass only) or accounting in terms of adjustments NGHGI compilation methods (e.g. to better align biochar inclusion). Methods such as biomass burial and bio-oil injection may also fall into this category.

- **Category 3 – Major challenges**. CDR methods in this category must overcome major MRV hurdles before integration into mainstream climate policy approaches. The challenges include additionality (e.g. IFM), measurement (SOC enhancement) and durability (SOC).

- **Category 4 – Significant barriers**. This category includes CDR methods which face major monitoring barriers, such as EW (challenge to identify and measure efficacy and to trace the fate and behaviour of EW products in the environment) and ocean-based CDR.

The clusters are shown schematically below (see Figure 3).

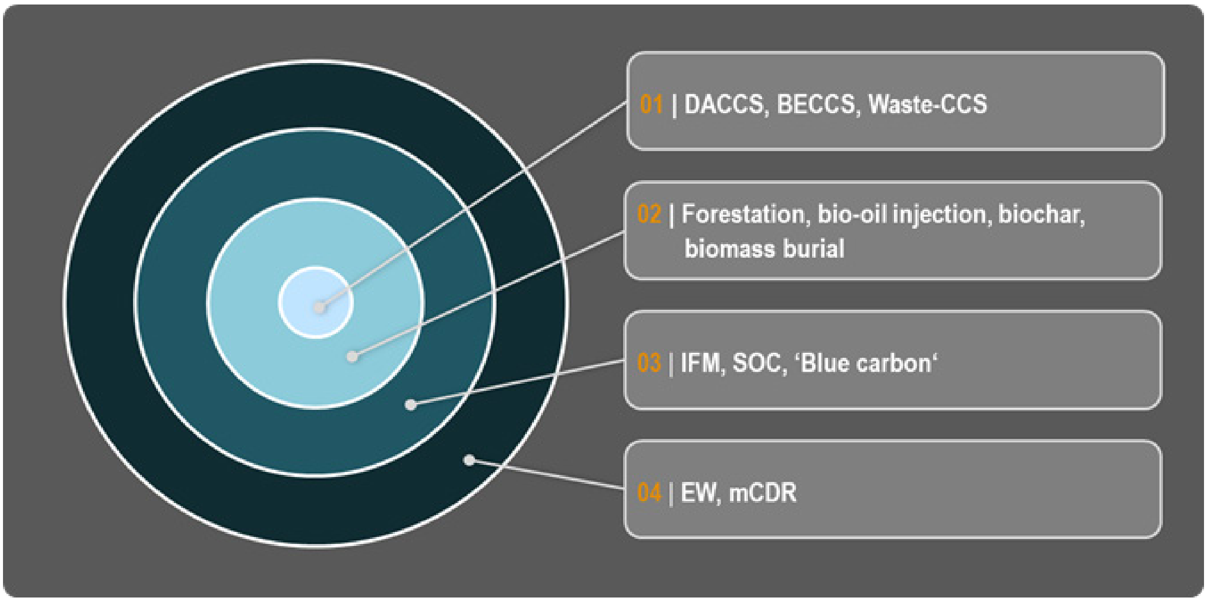

Figure 3 Clustering of 'MRV-ability' (mCDR = marine CDR = ocean-based CDR)

Expert Review Comments

11 expert reviewers from academia, industry and non-governmental organisations were invited to provide comments on the draft report, of which 6 submitted responses. The comments were generally positive, and the report was seen as a welcome addition, bringing clarity to CDR MRV issues and being one of the first and most comprehensive attempts to fill much needed gaps. Some of the more specific comments included:

- More clarity that accounting for removals in NGHGI and separately in corporate inventories is not double counting →A new section '4.3.3 Voluntary climate action, GHG accounting and climate-related claims' was added to the report.
- Range of comments on attributional vs consequential accounting → The text has been updated with reviewers' suggestions and more careful framing language has been chosen at the relevant points in the report, especially in and around Table 4.1.
- Recommendations concerning the inclusion of DACCS in IPCC inventory reporting guidelines → Those were not included, as considered potentially policy-prescriptive. Stronger referencing/mentioning of the IPCC Task Force in Inventories Methodology Report on CDR and CCS has been included.
- Questions regarding the assessment of environmental, technical and financial risks → Some are covered under the assessment criterium '04 Sustainability'. However, economic risks have not been assessed in this study, due to the challenges in characterising them.
- One reviewer disagreed with the clustering methodology and the findings for ocean-based CDR approaches. The contractor stood by their methodology and assessment for the delivery of the scope of this study. Thus, only minor changes were made.

Conclusions

The review set out herein highlights the momentum that has been garnered around CDR as a climate solution in a relatively short space of time. It also shows that markets are responding to the momentum by leveraging finance for CDR start-ups of many varieties, and by creating demand signals through corporate procurement programmes for the CDR credits these firms intend to supply. Reasons persist for being both positive and circumspect about the role of CDR in ambitious climate action: on the one hand, CDR approaches seem essential to achieving the Paris Agreement goals; on the other, CDR poses significant challenges for climate policymaking.

The technical review of CDR methods highlights that questions remain over the foundational science and/or social acceptance underpinning most CDR methods. For several, understanding their efficacy and efficiency, especially under a wide range of real-world conditions, remains uncertain (e.g. functionality in certain circumstances; GHG footprint of inputs in different situations). For others, durability can be a problem unless managed appropriately (e.g. soils and forests). Another group of methods face significant social acceptance and legal impediments that will likely hinder significantly scaled-up deployment (e.g. geological storage and ocean-based CDR). In all cases, such hurdles impact upon their availability and timeliness to scale to meet climate goals over the next 25 years or so. As such, the view that a portfolio of CDR methods is likely to be needed to meet the Paris Agreement goals is reaffirmed.

Our understanding of the efficacy of some CDR methods is hampered by observational challenges. For CDR methods such as SOC, EW and ocean-based CDR among others, challenges persist for monitoring CO_2 flux rates, C stock changes and the fate and behaviour of C carriers (e.g. bicarbonate) in the environment. Despite stoichiometric models indicating that several CDR methods can be expected to deliver a CO_2 drawdown effect, monitoring of field trials have in many cases been unable to corroborate these hypotheses.

The review of MRV for the various CDR methods clearly indicates that recent focus has almost exclusively been tilted towards developing project-based methodologies by which to certify and credit CDR activities. Such methods are inherently consequential, relying on a baseline scenario and crediting baseline to infer a level of net CO_2 removal being achieved by a given CDR activity.

The need for a baseline introduces significant variability due to the challenges in designing and implementing methods by which to determine a counterfactual or "what if" scenario at the level of an individual activity. Establishing counterfactuals is a notoriously difficult subject, and additionality testing applied in many crediting programmes to date has been subject to widespread criticism. So far, with the exception of the NZ emissions trading system (ETS), little attention has been given to the possibilities for attributional approaches to CDR that can avoid such challenges.

Yet compliance with the Paris Agreement will be based in the real, measured, attributes of the signatory Party countries, namely: their emissions and removals as compiled and reported in NGHGIs. This situation poses two critical issues for the current approach to CDR crediting or certification:

- **Policy utility**. If certified and/or credited CDR activities do not create a symmetrical and equivalent amount of CDR in the host country NGHGI – a problem that can be termed inventory visibility – then any policy designed to incentivise CDR projects will lack political utility for the host government. Furthermore, environmental integrity problems may arise where such certificates or credits allow an acquiring entity to make neutralisation claims, but such benefits are not also bestowed upon the country hosting such activities. These challenges could also be exacerbated by trans-boundary movements of products within CDR value chains, which could also compromise overall mitigation in global emissions (OMGE).

- **Long-term responsibility**. Host countries are ultimately the 'underwriter of last resort' for carbon reversal from most enhanced C sinks and reservoirs that result from CDR activities. The country should be monitoring these sinks and, where a reversal occurs, counting the CO_2 fluxes against their national climate targets (i.e. their nationally determined contribution (NDC)). However, seemingly to date the full implications of this arrangement have not been entirely realised. Better understanding over the liability for any carbon reversals may impair countries' willingness to host CDR activities, a problem that can be further exacerbated by inventory visibility. These risks need to be characterised and managed in order to support countries in accepting these arrangements.

Ocean-based CDR methods pose unique challenges in these regards; since the ocean C reservoir falls outside of national MRV frameworks, any CO_2 drawdown resulting from such methods will be neither visible in any country's NGHGI nor subject to any host country monitoring that could offer means to address liability for any carbon reversal. At the time of writing, further discussion of these important matters, and a more nuanced dialogue around approaches to address them, appears vital.

Recommendations

Further work could investigate CDR/CCS under the UNFCCC/Paris Agreement in more detail. It would draw from both this IEAGHG study on MRV for CDR as well as 2023-01 "Integrating CCS in international cooperation and carbon markets under Article 6 of the Paris Agreement" and aim to provide some guidance on how countries' pledges can be enhanced through collaboration and 'MRV'ed' in practice.

IEA Greenhouse Gas R&D Programme

Measurement, Reporting and Verification for Carbon Dioxide Removal

FINAL REPORT

Carbon Counts Company (UK) Ltd

June 2024

Measurement, reporting and verification for carbon dioxide removal

Final Report

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Disclaimer

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Acronyms and Abbreviations

AFOLU	Agriculture, forestry and other land use
A/R	Afforestation/reforestation
BC	Biochar
BECCS	Bioenergy with carbon capture and storage
BiCRS	Biomass carbon removal and storage
C	Carbon
CCP	Core Carbon Principles (IC-VCM)
CCS	Carbon dioxide capture and storage
CDM	Clean Development Mechanism
CDR	Carbon dioxide removal
COP	Conference of Parties to the UNFCCC
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRCF	EU Carbon Removals and Carbon Farming Certification
DAC	Direct air capture
DACS	Direct air capture with storage
EC mCDR	Electrochemical ocean CO_2 removal
ETS	Emissions trading system
EW	Enhanced weathering
GHG	Greenhouse gas
GHGI	GHG inventory [of emissions and removals]
HWP	Harvested wood products
ICP	Independent crediting programme
IC-VCM	Integrity Council for Voluntary Carbon Markets
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land use change and forestry
MRV	Measurement, reporting and verification
mCDR	Marine CDR (ocean-based CDR)
NDC	Nationally determined contribution
NGHGI	National GHG inventory [of emissions and removals]
OAE	Ocean alkalinity enhancement

OMGE	Overall mitigation in global emissions
OIMP	Other international mitigation purposes
PAMs	Policies and measures
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
VCMI	Voluntary Carbon Market Integrity Initiative

Executive Summary

About carbon dioxide removal and its drivers

The Paris Agreement's shift in emphasis away from a focus on emission reductions and towards net zero—that is, the balancing of atmospheric greenhouse gas (GHG) emissions by sources and removals by sinks in the second half of this century—has shone new light on the role that carbon dioxide removals (CDR) can play in meeting ambitious climate mitigation goals.

Alongside more conventional forms of nature-based carbon removal (e.g. forest, soil carbon), the past three to four years has witnessed a substantial growth in dialogue and on-the-ground activity around various novel CDR methods, albeit from a small base. Novel CDR methods include geological storage of CO_2 captured from the air or from biogenic sources ('DACS' and 'BECCS'), injection of biogenic waste oils into geologic formations, the conversion of biomass into relatively inert biochar and its storage as inorganic carbon in soil, the interment or sinking of organic biomass for storage in soils, freshwater or marine environments, and the use of ground-up rock to induce accelerated atmospheric CO_2 drawdown through terrestrial rock weathering or through changes in ocean chemistry.

The counting of removals as a balance against the ongoing emissions of both countries and companies points to a growing need to move towards CDR focussed offsetting strategies (Oxford Offsetting Principles; Allen et al., 2021). In the case of the second, voluntary carbon markets (VCM) are seeing rising interest in the acquisition of credits (or certificates) from CDR activities to substantiate private sector climate 'neutralisation' claims. On the supply-side, various independent crediting programmes (ICPs) are responding through the expansion of CDR certification methodologies and protocols, including through market entrants entirely dedicated to CDR (e.g. Puro.Earth, Isometric). These developments have led some observers to refer to a CDR boom over recent years.

At the time of writing, privately-run VCM credit procurement programmes have reached pre-agreements for the purchase of novel CDR credits in the order of several million tonnes CO_2. Prices are also robust, with offtake agreements reportedly exceeding US$1000 per tonne CO_2 for some novel CDR methods (e.g. for ocean alkalinity enhancement). Yet only a tiny fraction of credits from novel CDR activities have actually been delivered (mainly from biochar activities). Presently, conventional (nature-based) CDR remains as a significant part of the VCM supply base at much lower prices (US$1-3 per tonne CO_2).

Governments are also considering national policies and measures to support CDR in pursuit of Paris-aligned climate goals. The rapid expansion of CDR interests in the VCM is also attracting the attention of government regulators looking to establish harmonised quality standards by which to certify the net removals achieved by sink enhancement activities (e.g.

through the introduction of government operated CDR certification methodologies and tightened regulation of the nature of corporate climate-related claims).

Yet, while the opportunity for CDR market development remains potentially significant, foundational technical and measurability—or 'MRV-ability'—issues need to be resolved to build trust and confidence in the efficacy, efficiency, sustainability and durability of CDR methods.

Technical viability

An assessment of the technical characteristics of CDR is presented, based on the following CDR clusters: biological carbon (C) capture and storage; engineered geological CO_2 storage; engineered biological C storage; and, ocean-based CDR. The following evaluation criteria are applied: efficacy, efficiency, durability, sustainability, scalability and availability.

The technical assessment indicates that questions remain over the foundational science and social acceptance underpinning most CDR methods. For several methods, evidence of their efficacy and efficiency, especially under a wide range of real-world conditions, remains uncertain (e.g. functionality in certain circumstances; GHG footprint of system inputs in different situations). For others, durability can be problematic unless managed appropriately (e.g. soils and forests). Another group of methods face significant social acceptance and legal impediments that will likely pose challenges for significant deployment and scale-up (e.g. geological CO_2 storage and ocean-based CDR).

A comparative technical assessment summary is presented below (Figure ES-1). The results suggest that all CDR clusters face deployment challenges that impair any single method to significantly contribute towards climate mitigation by mid-century or shortly thereafter. The results reaffirm the widely held view that a portfolio of CDR will be necessary to deliver meaningful climate action over the near- to mid-term.

Figure ES-1 Summary results of CDR evaluation

MRV-ability

The nature and challenges of CDR measurement, reporting and verification (MRV), the range of potential MRV approaches, and issues for accounting for MRV actions against climate targets are reviewed.

Identified challenges include the accuracy of measurement techniques applicable to various CDR methods, which spans relatively accurate direct mass flow metering (subsurface injection of supercritical CO_2) or mass weight measurement (e.g. biomass burial) to more uncertain indirect net flux estimates based on measuring C stock changes over time (e.g. biological carbon sinks). Other identified MRV challenges include baseline development, fair and consistent means to determine additionality, the management of non-permanence (durability) and approaches to mitigate the risks of carbon reversal (i.e. the longer-term release and re-emission of C stored in enhanced C reservoirs).

CDR MRV is characterised across two accounting frames:

1. **Project-based approaches**. These seek to identify and measure GHG effects resulting from discrete management interventions. The scope of MRV and accounting is usually based on full-chain, lifecycle, consequential methods with the goal of linking causality to a particular management action or intervention. Causality is inferred through a comparison of the actual GHG emissions and removals of an activity with that of a notional estimate of how GHG emissions and removals would have evolved absent of the intervention (i.e. a counterfactual baseline); and
2. **Inventory compilation approaches**. These seek to consistently and comparably measure GHG performance of a reporting entity. The scope of this more attributional or allocational MRV and accounting method is generally limited to the organisational boundary of the reporting entity with the goal of tracking its performance over time. Performance is inferred through changes in GHG emissions and removals relative to a selected base year.

The surge in private demand for carbon credits in recent years has focussed CDR MRV on project-based approaches. These seek to quantify and certify the net GHG effects of discrete CDR actions with a view to supplying carbon credits, rather than the measurement of an entity's (or land parcel's) net GHG removal performance over time. A review of the methodological features for project-based approaches for CDR methods is provided covering boundaries, leakage, baselines, additionality, monitoring, non-permanence and approaches to manage C reversal risk.

Notably, the need for a baseline in project-based approaches introduces significant methodological variability; there are substantial challenges in designing and consistently implementing methods by which to determine counterfactual or "what if" scenarios at the level of individual project activities. Establishing counterfactual scenarios is a notoriously difficult subject, hampered by information asymmetry. Additionality testing applied in many crediting programmes to date has been subject to widespread post hoc criticism. So far, with the exception of the New Zealand emissions trading scheme, little attention has been given to the possibilities for attributional approaches to CDR that could avoid some of the accounting challenges faced by project-based approaches (i.e. application of site level quantification methodologies with narrow boundaries).

Project-based MRV is also considered in respect of linkages to the attributional national GHG inventory (NGHGI) systems that are used to measure and track the contributions of countries towards achieving the Paris Agreement's goal. The assessment indicates that significant asymmetries can arise between what is MRV'd, certified and credited at a project level and whether and how the same action may be recorded a host country's NGHGI. Issues can arise due both to differences in the methodologies (e.g. boundaries; monitoring differences; variations in the calculation methods) and the absence of monitoring and/or methodologies for some CDR methods (e.g. lack of NGHGI methods for enhanced rock weathering). These can collectively create what has been termed an 'inventory visibility' problem.

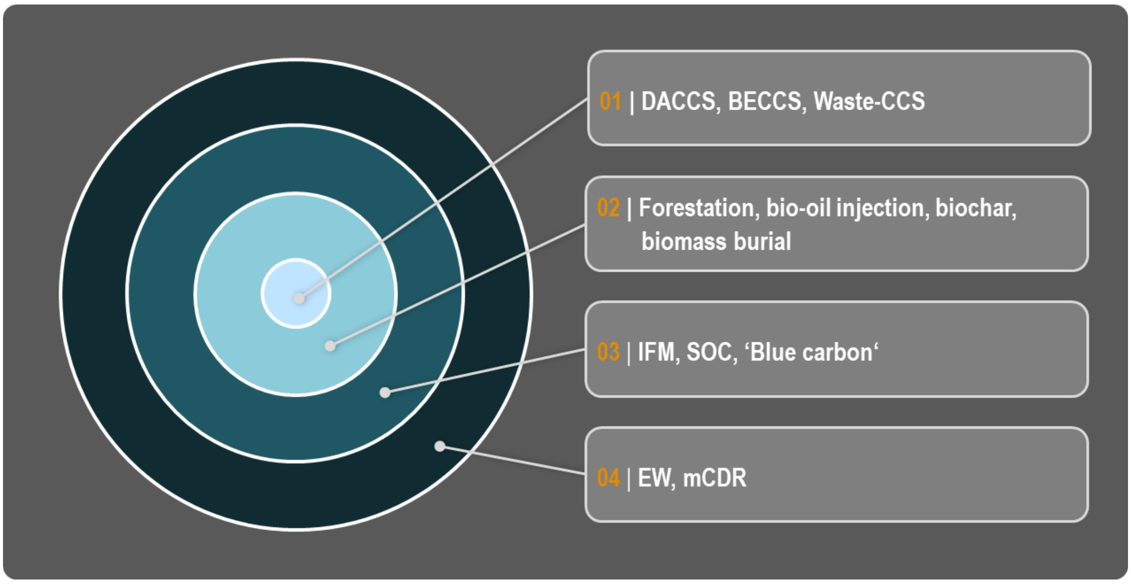
The potential asymmetries pose two critical issues for current approaches to CDR crediting or certification:

- **Policy utility**. If certified and/or credited CDR activities do not create a symmetrical and equivalent amount of CDR in the host country NGHGI, then any policy designed to incentivise CDR projects will lack political utility for the host government. Environmental integrity problems will arise where CDR certificates or credits allow an acquiring entity to make neutralisation claims against its MRV'd emissions, but such benefits are not equally bestowed upon the country hosting the activity. These challenges could also be exacerbated by transboundary movements of products within CDR value chains (i.e. creation of emissions in one country to drive removals in another), effects which could also compromise the overall mitigation in global emissions required for unit trading under the Paris Agreement's Article 6.
- **Long-term responsibility**. Host countries are ultimately the underwriter of last resort for any C reversal from most enhanced C reservoirs produced by CDR activities. The host country should be monitoring these reservoirs and, where a C reversal occurs, counting the CO_2 fluxes against their national climate targets (i.e. their nationally determined contribution; NDC). To date, the full implications of this arrangement have seemingly not been sufficiently appreciated nor confronted. Improvements in understanding of the potential liability for any C reversals may impair countries' willingness to host CDR activities, a problem that can be further exacerbated by inventory visibility. These risks need to be characterised and managed so as to assist countries in managing these arrangements.

Ocean-based CDR methods pose unique challenges in these regards. Since the planetary oceanic C reservoir largely falls outside the scope of national MRV frameworks, any CO_2 drawdown resulting from such methods will neither be visible in any country's NGHGI nor subject to any host country monitoring and reporting in an NGHGI in the event of CO_2 outgassing (i.e. emissions).

A clustering of CDR method MRV-ability is provided (Figure ES-2). This is based on the MRV-ability criteria of boundary setting, leakage determination, monitoring, non-permanence and accounting. Those CDR methods closer to the centre of the chart face fewer MRV challenges relative to those on the outer ring.

Figure ES-2 Clustering of MRV-ability



1 Introduction

The concept of 'net zero' is the framing paradigm for climate action in these times. Net zero draws from the realisation that global warming is a function of the cumulative stock of greenhouse gases (GHG) in the atmosphere—especially long-lived climate forcing pollutants like CO_2—rather than just the rate at which emissions are being added thereto (Allen et al. 2009; Matthews et al. 2009; Zickfeld et al. 2009; Meinshausen et al. 2009).

Whereas the 1997 Kyoto Protocol primarily focused on quantified emission limitation and reduction goals, the 2015 Paris Agreement, in setting the ambition to limit the mean global temperature increase to well within 2°C and pursue efforts to limit the temperature increase to within 1.5°C, calls upon all signatory Parties to:

> "...aim to reach global peaking of greenhouse gas emissions as soon as possible…and to undertake rapid reductions thereafter in accordance with best available science, so as to **achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases** in the second half of this century" (Article 4.1)

Countries should thus seek to achieve net zero global emissions within the next 50 years or so.

The subtle shift in emphasis away from a focus on reducing and eliminating GHG emissions (as in the quantified emission limitation and reduction targets of the Kyoto Protocol) towards the net zero frame has shone a new light on the role and potential of GHG removal (GGR) or carbon dioxide (CO_2) removal (CDR) in climate change mitigation.[1] Today, there is growing acceptance that CDR methods are needed to offset some ongoing, hard-to-abate, residual anthropogenic GHG emission sources in order to achieve, and thereafter maintain, a state of net zero (IPCC 2022).

A switch in ambition towards net zero goals is playing out on several fronts. According to Fankhauser et al. (2022), at the time of their writing more than 120 countries had variously pledged to achieve net zero by mid-century or within 20 to 30 years thereafter—a group which now includes China, India, the U.S., the European Union (EU), Russia and Saudi Arabia. The *Net Zero Stocktake* report (Net Zero Tracker 2023) indicates the establishment of net zero organizational targets by almost 150 regional governments, 250 cities and 1000 companies. Notwithstanding the potentially variable interpretations of net zero (see e.g. Fankhauser et al. 2022), recent evaluations suggest that almost 90% of global GHG emissions are covered by some sort of net zero target today (Net Zero Tracker 2023; Climate Action Tracker 2023).

The topic of CDR is, however, not new to the climate policy discourse. Experiences with the governance and accounting of emissions and removals arising from land use, land use change

[1] Hereafter we use the term 'CDR' in this report and focus only on CO_2 removals methods.

and forestry (LULUCF) and the enhancement of geological reservoirs using carbon capture and storage (CCS) were important and contentious features of the Kyoto Protocol negotiations (e.g. Höhne et al. 2007; Dixon et al. 2013; Dooley and Gupta 2017).[2] These experiences provide valuable lessons that can be drawn upon to inform today's policy approaches. Net zero framing therefore rather provides CDR with renewed momentum, building upon both the longstanding need to better manage terrestrial carbon (C) stocks through conservation and enhancement, and to develop other, novel, human induced CDR methods that can enhance a range of planetary C sinks and reservoirs.

The changing emphasis around CDR is clear in today's climate change policy discourse. Since the entry into operation of the Paris Agreement in 2020 there has been a steady expansion of the voluntary carbon market (VCM; e.g. drawing form the Taskforce for Scaling Voluntary Carbon Markets; TSVCM 2021; Box 1-1) and therein a growing recognition that offsetting of emissions using credits originated from emission reduction or emissions avoidance activities alone will not deliver a net zero outcome (e.g. Allen et al. 2020; Smith 2020).

Box 1-1 The Voluntary Carbon Market

In the voluntary carbon market (VCM), developers of project activities that avoid, reduce or remove emissions can apply to registries for the issuance of carbon credits (e.g. the UNFCCC clean development mechanism, and those operated by independent crediting programmes (ICPs) such as Verra/VCS, Gold Standard, ACR, Puro.earth etc). The methodologies for certifying and crediting these actions are established by the UNFCCC and/or ICPs covering various measurement, reporting and verification (MRV) requirements and usually taking account of the full chain of emissions and removals of these project activities relative to a counterfactual, baseline, scenario (see Box 1-2). Once an activity is approved and registered, and ongoing MRV shows reductions or removals, credits may be issued to the developer.

The credits can be voluntarily acquired and cancelled by entities to be counted against their own reported GHG emissions. This is termed offsetting, balancing, compensation or neutralisation depending on the approach (although offsetting has become less common). In general, 'compensation' involves acquisition of carbon credits from emission reduction activities beyond the value chain of the acquiring organisation, while 'neutralisation' refers to the acquisition of carbon credits originating from CDR activities. The Science-based Targets Initiative (SBTi) and Voluntary Carbon Market Integrity Initiative (VCMI) are two of various organisations seeking to guide such actions. They may be consulted to clarify the types of claims that organisations acquiring and cancelling carbon credits may wish to make.

In the past three years, an increasing number of CDR concepts, reports, platforms, and, increasingly and importantly, policy actions, are focussed on specifically addressing and/or promoting CDR.

In 2022, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), in its 6th Assessment Report (AR6; IPCC 2022), dedicated significant new text to the cross-cutting topic of CDR (Babiker et al. 2022). Some other recent examples of scholarly literature and influential reports exploring the CDR field include:

- State of Carbon Dioxide Removal, 1st Edition and 2nd Edition ((Smith et al. 2023; Smith et al. 2024)

[2] See also: https://unfccc.int/topics/land-use/workstreams/lulucf-under-the-kyoto-protocol/reporting-and-accounting-of-lulucf-activities-under-the-kyoto-protocol

- Emissions Gap Report 2023 (new chapter on CDR) (UNEP 2023)
- Roads to Removal: Options for Carbon Dioxide Removal in the United States (LLNL 2023)
- Carbon Dioxide Removal: Best-Practice Guidelines (WEF 2024)
- Carbon removals: How to scale a new gigaton industry (McKinsey & Co 2023)
- Strengthening MRV standards for greenhouse gas removals to improve climate change governance (Mercer and Burke 2023)
- Reaching climate objectives: the role of carbon dioxide removals (Energy Transitions Commission 2021)

Today, many research groups are working to integrate a wider range of novel CDR methods into the integrated assessment models (IAMs) that are used to inform climate action decision-making. CDR-specific policy is also evolving, including at international (UNFCCC) and national levels (in particular in the U.S., the European Union (EU), Sweden, Denmark, Switzerland and the UK among others; see Section 2.3.2).

Nevertheless, while there is clear momentum in the CDR field, a number of challenges persist. One such issue receiving particular attention is the need for robust quantification methodologies and effective measurement, reporting and verification (MRV) that can accurately determine the net amounts of C/CO_2 removed by various human-induced CDR activities (Box 1-1). Assurance over the efficacy, efficiency, safety and ongoing durability of C stored in enhanced reservoirs is essential to build confidence in CDR methods and to foster further development.

A number of CDR MRV efforts are underway today by private and public actors in both the VCM and regulated carbon market (see Sections 2.3.1 and 2.3.2). The discussions and outcomes from these processes will have clear ramifications for the way in which MRV approaches and methodologies will be used to calculate and verify CDR actions in future. Yet, at the time of writing, much debate and uncertainty remains regarding the best means of doing so.

1.1 Aim and purpose of this report

Taking account of the backdrop outlined, the recent and extensive extant literature on the subject, and the complex, evolving, CDR ecosystem, this report sets out to assess some of the specific MRV and GHG accounting aspects relating to CDR.

The first part of the report considers the current technical status of various proven and hypothesized CDR methods. The second part assesses the 'MRV-ability' of a range of CDR methods. The findings are structured as follows:

Section 2 provides a high-level summary outlook for CDR, drawing upon recent literature.

Section 3 provides a more synthesized technical characterisation and assessment of CDR methods. The appraisal fiches standing behind the assessment are set out in Annex A.

Section 4 provides a review of MRV features and GHG accounting aspects of the assessed CDR methods and provides a broad evaluation of "MRV-ability".

Section 5 draws together the results into a structured conclusion and areas for further consideration.

Box 1-2 Measurement, reporting and verification (MRV) in climate policy

Measurement, reporting and verification (MRV; sometimes also monitoring, reporting and verification) in climate policy relates to the ability to reliably, transparently, comprehensively and accurately monitor, measure, report and verify GHG emissions and removals at an organisational, programme, project, product or value chain level. MRV is critical to informing and tracking the effectiveness of actions to mitigate climate change and to value such services accordingly (or to penalise emitters accordingly).

The term 'MRV' originates from Articles 4 and 12 of the UNFCCC, which oblige all Parties to develop, periodically update, publish and make available to the Conference of Parties (COP), national inventories of anthropogenic GHG emissions by sources and removals by sinks using comparable methodologies as agreed by the COP (UNFCCC 2014). Since the UNFCCC was agreed in 1992, MRV has evolved in response to the enhanced accounting needs presented by the Kyoto Protocol's *quantified* emission limitation and reduction obligations (QELROs) and its flexibility mechanisms. Today, MRV remains a cornerstone of the Paris Agreement's accounting and cooperation mechanisms (e.g. the enhanced transparency framework in Article 13 and cooperation in Article 6), as well as for governments implementing national climate policies and measures (PAMs) in pursuit of climate mitigation goals pledged in nationally determined contributions (NDC) under the Paris Agreement.

In reporting organisational GHG inventories, MRV is underpinned by the 'TACCC' principles: (transparency, accuracy, completeness, comparability, consistency), and the assessment of the quality of the reported results of measurement (i.e. verification). For UNFCCC Parties, methodologies are set out in Intergovernmental Panel on Climate Change (IPCC) Guidelines (e.g. *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *2019 Refinement* thereto; IPCC 2006; IPCC 2019). MRV by non-state actors is typically informed by the suite of 'GHG Protocol' guidance (e.g. WBCSD/WRI 2004).

MRV is also increasingly considered in respect of the quality of credits delivered by specific, definable, activities within project-based (or baseline-and-credit) mechanisms. Project-based accounting methodologies generally require that creditable actions be, inter alia, real, measurable, additional, not resulting in leakage, not double-counted, and permanent. Therein:

- Real means that reductions or removals actually result from a specific management intervention—or activity—and cannot simply be fabricated through falsification of facts, gaming or regulatory arbitrage.
- Measurable means that the GHG effects (positive or negative) attributable to an activity can be correctly identified, measured and quantified with a high degree of certainty (see Section 4.2.4).
- Additional means that an activity leads to emission reductions or removals that exceed what would have otherwise happened absent of the availability of crediting for the activity (sometimes referred to as the business-as-usual scenario; see Section 4.2.3).
- Leakage refers to situations where a credited activity poses the risk of creating new sources of emissions outside of the control of the operating entity and the defined activity boundary (and therefore beyond what is measured and counted within the scope of crediting), but which are attributable to the activity (see Section 4.2.2).
- Double counting refers to the risk that the activity is awarded for the same action twice, and that in doing so, potentially leads to more than a single claim on the certified emission reductions or removals achieved (sometimes also incorporating double claiming or double issuance).

- **Permanent** means the achievement of durable storage of carbon away from the atmosphere for periods of time relevant to the mitigation of dangerous climate change (e.g. multi-century timescales, given the residence time of CO_2 in the atmosphere; see Section 4.2.5)

These requirements may be translated into methodologies that can be used to calculate emission reductions or removals generated by specific activities (consisting of components such as boundaries, leakage, baselines, additionality and monitoring; Section 4.2). These methodological frameworks also include various approaches to manage the risk of non-permanence of C storage in enhanced reservoirs, to allocate responsibility in the event of carbon reversal (i.e. loss/fluxes of C from an enhanced reservoir and its release to the atmosphere as CO_2), and to limit double counting.

Alongside experiences under the UN's joint implementation (JI) and clean development mechanism (CDM) programmes, methodologies, protocols and standards have also evolved across a range of ICP platforms in the VCM, with a marked acceleration over recent years.

Considerations for 'MRV-ability' in this report encompass all of these aspects.

2 About Carbon Dioxide Removal (CDR)

2.1 Scoping and defining CDR methods

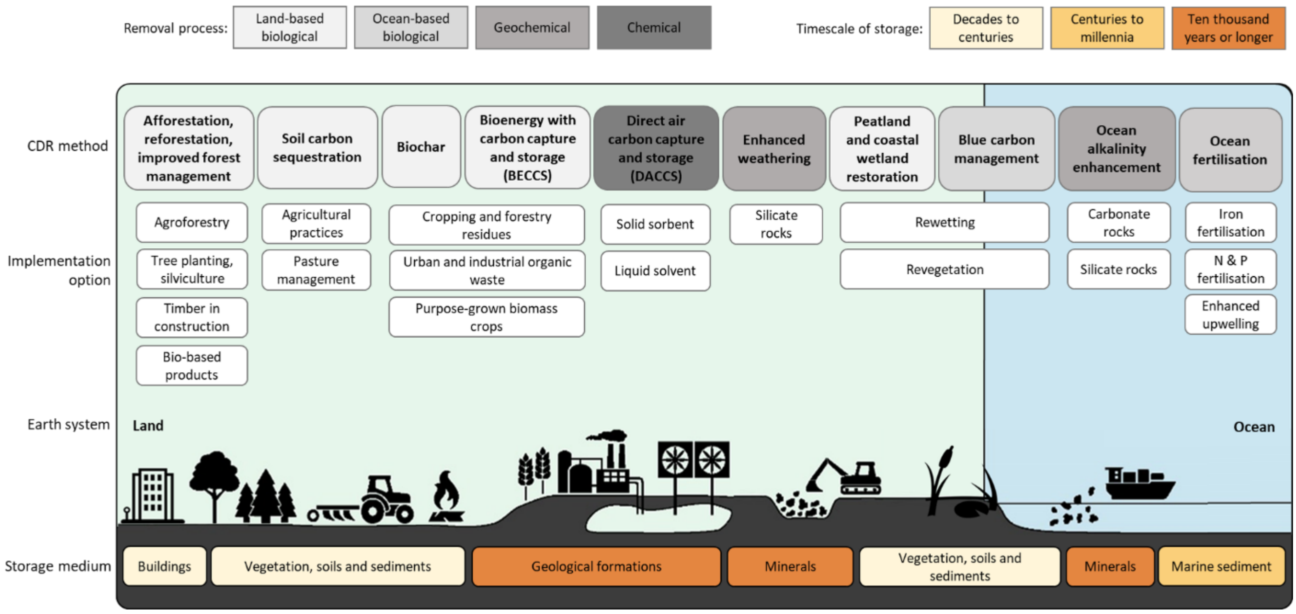
The Intergovernmental Panel on Climate Change (IPCC) describes CDR as:

> "Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACS), but excludes natural CO_2 uptake not directly caused by human activities." (Babiker et al. 2022, p.1261; IPCC 2022, p.1796)

This definition is now widely applied in climate discourse. Babiker et al. (2022) also refer to the various techniques for removing CO_2 from the atmosphere as CDR "methods", which is also used in this report.

The diagram below, taken from IPCC (2022) and drawing from Minx et al. (2018), is widely used to rapidly convey the scope and diversity of CDR methods.

Figure 2-1 Taxonomy of CDR



Notes: Main implementation options are included for each CDR method. Specific land-based implementation options can be associated with several CDR methods (e.g. agroforestry can support soil carbon sequestration and provide biomass for biochar or BECCS). Source: Babiker et al. (2022), adapted from Minx et al. (2018).

The scope of this study covers the following conventional and novel CDR methods:

- Afforestation/reforestation (A/R) ('forestation') and forest management
- Soil organic carbon (SOC) including wetlands (blue carbon)

(conventional, nature-based)

- Bioenergy with carbon capture and geological storage (BECCS)[3]
- Direct air capture and geological storage (DACS)[3]
- Enhanced rock weathering (ERW)
- Biochar (BC)
- Bio-oil injection and biomass burial
- Ocean-based (marine) carbon dioxide removal (mCDR):
    - o coastal enhanced weathering (CEW), ocean alkalinity enhancement (OAE), ocean fertilization and oceanic CO_2 removal and storage.

(novel, engineered)

Detailed assessment fiches for each CDR method are presented in Annex A. Therein, an alternative classification approach to that of Minx et al. (2018) and Babiker et al. (2022) is applied, based upon the terrestrial pool where the carbon is stored. For example:

- A significant proportion of CO_2 anticipated to be captured through 'alkali CDR' or enhanced weathering (EW) methods such as ERW, CEW and OAE will ultimately reside in the oceanic water column as dissolved bicarbonate (HCO_3^-) (i.e. ocean C stock). Over time, some of the bicarbonate in the water column can be synthesized by marine organisms and stored in ocean sediments as calcium carbonate (so, ultimately, as geological C stocks, rather than just 'minerals')
- Terrestrial C stocks may be enhanced as above- and below-ground biomass, soil organic carbon, or soil inorganic carbon (rather than the generic 'vegetation, soils and sediments')—see Section 3.1.1.

The greater specificity in describing the C pool used for storage can be useful for considering the features of different CDR methods, and in particular, their MRV-ability.

2.2 The opportunity for CDR

The enhanced focus on the role of CDR in the IPCC AR6 brought to the fore the scale of both the opportunity and challenges. For the opportunity, Chapter 12 of the AR6 (Babiker et al. 2022) and the *State of Carbon Dioxide Removal* (1st edition) (SoCDR; Smith et al. 2023) both recap upon three core functions that CDR can play in progressing climate action:

- First, CDR can reduce net emissions in the near term.
- Second, CDR can offset unavoidable emissions from hard-to-abate sectors to achieve net zero emissions in the medium term.
- Third, if removals exceed emissions, CDR can achieve net-negative emissions in the longer term. At the global level, this could be used to bring temperatures down in a scenario where global temperature increase exceeds acceptable levels (known as 'overshoot' scenarios).

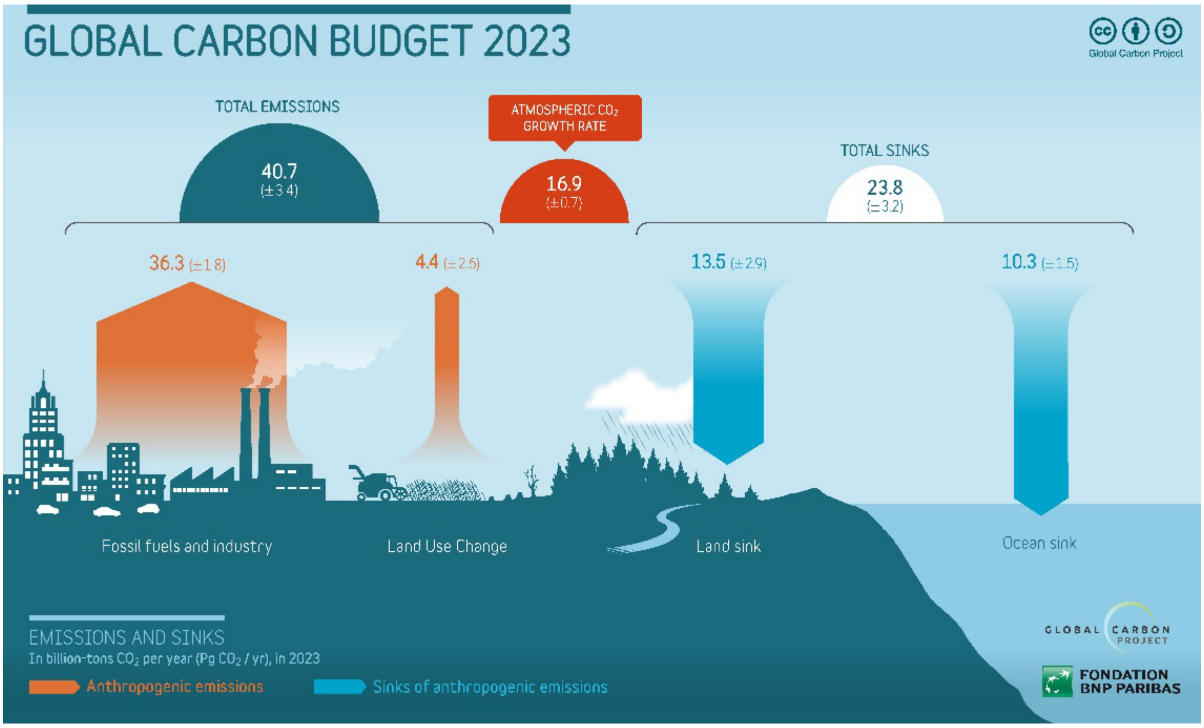
[3] Including both sedimentary reservoir storage and mineral storage in mafic and ultramafic rock.

In fulfilling these roles, synthesized findings of the IPCC AR6 suggest that various CDR methods will need to remove around 740 $GtCO_2$ (range 420-1100) from the atmosphere by 2100 to limit global warming to 1.5°C with no or limited overshoot (IPCC 2022). This decreases only slightly to 630 $GtCO_2$ (range 440-1100) by 2100 for a 2°C temperature increase limitation goal.

At the time of achieving net zero CO_2, CDR levels could range between **5.5 and 16 $GtCO_2$/year** under 1.5°C pathways (at around mid-century) and between **6.8 and 16 $GtCO_2$/year** in 2°C pathways (around two decades after mid-century under the 1.5°C pathway) (Smith et al. 2023). According to analysis by Smith et al. (2023), almost all scenarios applied in the AR6 envisage a period of net-negative emissions after mid-century.

For context, global emissions in 2022 from fossil sources and land use change are estimated to be 40.7 $GtCO_2$/year (±3.4 Gt), with CO_2 removals by the Earth's terrestrial (land) and ocean sink totalling 23.8 $GtCO_2$/year (±3.2 Gt, Friedlingstein et al. 2023 — the Global Carbon Budget). The result is an annual addition of CO_2 to the atmosphere of around 16 $GtCO_2$/year (Figure 2-2).

Figure 2-2 Estimated planetary CO_2 flows in 2023



Source: Global Carbon Atlas (https://globalcarbonatlas.org/budgets/carbon-budget/)

Efforts have been made to quantify current levels of human-induced CO_2 removal flows relative to naturally occurring uptake in the Earth's carbon cycle (from Powis et al. 2023 and Friedlingstein et al. 2023). Analysis suggests the following human-induced actions:

- **1.9850 $GtCO_2$/year** by conventional CDR (forestation)
- **0.0023 $GtCO_2$/year** by novel CDR methods, consisting

- 1.82 $MtCO_2$/year by BECCS;
- 0.5 $MtCO_2$/year by biochar production;
- 0.01 $MtCO_2$/year by other approaches (DACS, mineralization, aquatic biomass growth, and others).[4]

Excluding the oceanic C sink, the balance of 11 $GtCO_2$/year is assumed to arise from naturally occurring, non-human induced, terrestrial CDR.[5] Powis et al. (2023) note that approximately 207 $MtCO_2$/year of land-based removals (10.4% of human induced flows) are accounted for in registered conventional, land based, sink enhancement projects, which they suggest indicates that the vast bulk of CDR is being generated unintentionally. On the other hand, some of the human-induced CDR can also be attributed to other, non-market based, climate PAMs (e.g. forestry and land use policies and sustainable or carbon farming programmes, for example, the EU's LULUCF Regulation). Notably, Friedlingstein et al. (2023) estimate that emissions from forest management in 2022 were about 0.8 $GtCO_2$/year (i.e. emissions from harvesting being higher than removal by regrowth).

The latest data on global C flows clearly indicate a significant 'CDR gap', that is: the difference between the current rate of CO_2 removal and future CDR needs aligned to Paris temperature limitation goals. In these respects, Smith et al. (2023) attempted a first indicative forward-looking estimate of the size of the CDR gap using a variety of sources. Drawing on Paris-aligned mitigation scenarios and the pledged CDR actions of countries,[6] they estimate derived median estimates of a CDR gap of, respectively, 5 $GtCO_2$/year and 2.5 $GtCO_2$/year in 2050 for conventional and novel CDR (Smith et al. 2023).

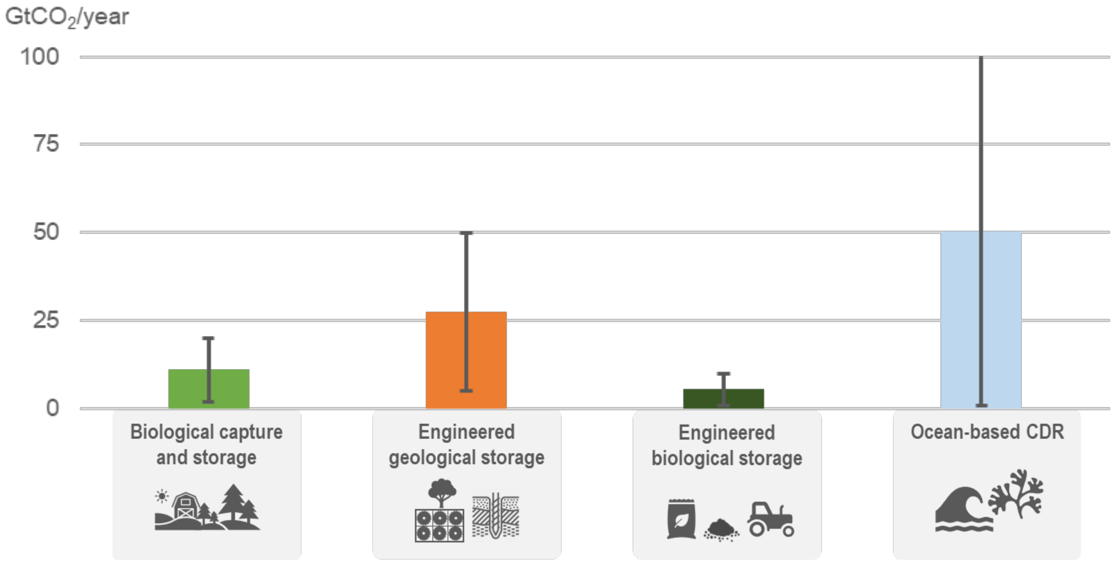
2.3 The outlook for CDR

The need to increase human-induced CDR—both conventional and novel—will be an increasingly important part of global action to address the Earth's warming climate. Theoretically, significant potential exists to do so. Estimates of CDR technical potential in the literature range from 5.5 to 11 $GtCO_2$ in 2050 (Lenton 2014) to 7.5 to 19.1 $GtCO_2$ of 'sustainable' CDR by 2050 (McKinsey 2023).

Cumulative totals of estimated technical potential for individual CDR methods range between 9 to 50 $GtCO_2$/year (low to mid) to or even >100 $GtCO_2$/year at upper end of published ranges (see Annex A; Figure 2-3). These are unconstrained estimates that do not take account of socio-economic or legal impediments, nor any possible interactions and effects that may arise between the various CDR methods.

[4] The data of Powis et al.(2023) differ to that of Friedlingstein et al.(2023) as the latter attribute BECCS and biochar removal to 'transfers of carbon stock between non-atmospheric reservoirs', rather than CDR per se.
[5] Notably, Smith et al.(2023) indicate that CDR on managed land reported in national GHG inventories averaged around 6.4 ± 2.8 $GtCO_2$/year for the period 2000-2020, with the difference attributable to the different methodologies employed in scientific analysis compared to national GHG inventory compilation.
[6] As set out in NDCs and long-term low emission development strategies (LT-LEDs).

Figure 2-3 CDR technical potential by sink type



Source: analysis in Annex A

Efforts have been made to further quantify future CDR deployment rates. In the near-term, expectations for increases in human-induced CDR stand at around 11.8 $MtCO_2$ by the end of 2024 and almost double this by 2030 (22.8 $MtCO_2$; Powis et al. 2023). The former is almost exclusively attributed to the completion of the *Summit Carbon Solutions* BECCS project,[7] while the latter incorporates several large developments including two BECCS plants from *Drax* and one of *1PointFive* / *Carbon Engineering's* megaton capacity DACS plants in the U.S. More recent announcements since the publication of Powis et al (2023) include a *Climeworks* DAC plant in the megatonne range by 2030.[8] Over a similar timeframe, the annual amount of novel CDR involving methods other than BECCS and DACS is forecast to remain well below 1 $MtCO_2$/year (Powis et al. 2023). Thus, geological CO_2 storage looks set to dominate the CDR scene pre-2030.

Over the longer-term, suggestions are that the current CDR deployment targets of companies and industry groups is generally well-aligned with pathways to achieving mid-century CDR potentials, particularly for DACS and biochar (Smith et al. 2023). The same report also notes that these deployment rates are, however, five orders of magnitude smaller than the mid-century technical potentials.

The levels of CDR needed to meet Paris goals coupled to the size of the estimated 'CDR gap' indicate that significant commercial opportunities exist for CDR entrepreneurialism. Indeed, according to several leading authorities, we may already be experiencing a 'carbon removal boom' (Time 2022; Economist 2023). Analysts such as McKinsey speculate that the world is gearing up for a billion-dollar, gigaton scale, industry that could be worth up to $1.2 trillion by

[7] Which will bring together 30 coupled ethanol-production/BECCS plants with geological storage
[8] Project Cypress DAC Hub (https://climeworks.com/news/project-cypress-team-awarded-funding-from-us-doe)

2050 if net zero levels are to be met (McKinsey 2023). In these respects, Smith et al.(2023) suggest that:

> "Growing from the current level to maximum mid-century potential implies an exponential growth rate of over 50% per year. That exceeds most previous technologies, but not all (such as the production of liberty ships in the United States during World War Two and worldwide computing growth)." (p. 39)

The growth of CDR entrepreneurialism and commercial interests is evidenced by a nascent but fast-growing CDR ecosystem (Box 2-1; Figure 2-1).

Box 2-1 The emerging CDR ecosystem

Recent years have seen a rapid expansion of climate action built almost exclusively around CDR. Clusters within this include:

- **Developers of CDR projects and programmes of activities, suppliers of removal credits to the carbon market,[9] and enablers and facilitators of these actions.** A growing number of start-up companies are exploring the opportunities to test, prove, deploy and scale-up CDR actions. The breadth and depth of new entrants is significant, and too large to capture here (several of the firms are listed in the fiches in Annex A). An array of enablers and facilitators are helping to build confidence in these actions through provision of human capital, technical expertise and supporting products (e.g. brokerage, insurance).
- **ICPs, marketplaces, intermediaries and standard setters.** Many new brokerage services offer support to organisations wishing to 'neutralise' their emissions through the acquisition and retirement of CDR credits.[10] This includes a diverse selection of actors such as specialist VCM ICPs dedicated to CDR (e.g. Puro.earth, Nori, Isometric), other VCM ICPs crediting both reductions and removals (e.g. Verra, ACR< Gold Standard, GCC), and intermediaries dedicated to CDR actions (e.g. Carbonfuture, Supercritical, C-Capsule). These actions are underpinned by both general MRV standards (e.g. IPCC Guidelines) and specific methodological approaches dedicated to CDR (e.g. VCM and the EU Carbon Removal and Carbon Farming Certification; CRCF)[11]. Several standard setters and academics are also guiding corporate climate-related action towards CDR (e.g. SBTi, ISO Net Zero Standard; Oxford Offsetting Principles). The emerging VCM governance framework under the Integrity Council for the Voluntary Carbon Market (IC-VCM)[12] and the VCMI[13] also include CDR activities within their ambit. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the UNFCCC Article 6.4 Supervisory Body also provide important benchmarks for emergent crediting programmes that encompass CDR.
- **Investors and funders.** A number of firms and government funds are backing nascent CDR methods (including BECCS, DACS, biochar, enhanced weathering and marine CDR). Some of the funds are channelled directly to project developers (e.g. Lowercarbon Capital funding of Running Tide; European Commission funding of Stockholm Exergi), some is channelled through bilateral credit offtake agreements including through 'buyers' clubs' (e.g. the advanced market commitment of Frontier, NextGen or the First Movers Coalition), some is channelled through approaches such as prizes (e.g. the U.S. DOE DAC prize) and some through tax credits (e.g. U.S. 45Q tax credit for DACS and BECCS).
- **Buyers and users committed to CDR.** On the demand side, a number of corporations—including the buyers' clubs mentioned above—are seeking to acquire CDR credits to satisfy corporate climate commitments (e.g. Microsoft;

[9] The carbon market here encompasses the VCM and compliance-based programmes such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and emerging government-to-government trades of mitigation outcomes for use towards nationally determined contributions (NDCs) under Article 6.2 of the Paris Agreement. The nascent compliance markets are making use of credits originated under ICPs and the related standards and methodologies.

[10] Generally, 'neutralisation' refers to the acquisition and cancellation by organisations of carbon credits exclusively from carbon removal activities so as to potentially support 'climate neutrality' claims. The approach differs from 'compensation', involving the acquisition of emission reduction credits. Readers are referred to the latest Science-based Targets Initiative (SBTi) and VCMI guidance for clarification of the types of claims organisations acquiring and cancelling credits may wish to make.

[11] Formerly, the EU Carbon Removal Certification Framework (CRCF).

[12] Custodian of the Core Carbon Principles guiding credit origination on the supply side of the VCM.

[13] Custodian of the Claims Code of Practice for carbon credits on the demand side of the VCM.

Shopify; Stripe; Swiss Re; Klarna). An increasing number of bilateral agreements are emerging (e.g. 1PointFive agreements with Airbus and ANA). Climeworks—a DAC firm—employs a direct-to-user sales approach.

- Academia and advisory with a strong presence in the CDR space. While many organisations can be counted within this group, several specialist centres and research clusters have emerged in various parts of the world—primarily in North America and Europe.
- Advocacy and influencer groups. The emergence of a new CDR sector has brought about the establishment of several advocacy and influencer groups that are seeking to shape the political and social landscape surrounding CDR methods. This includes dedicated groups in North America (e.g. Carbon 180; Carbon Removal Alliance; Carbon Business Council; Carbon Removal Canada), Europe (e.g. Negative Emissions Platform; Carbon Gap; DVNE; AFEN) and internationally (all). These actors are operating alongside long-standing groups that have advocate more widely for establishment of high integrity carbon markets (e.g. IETA; ICROA).

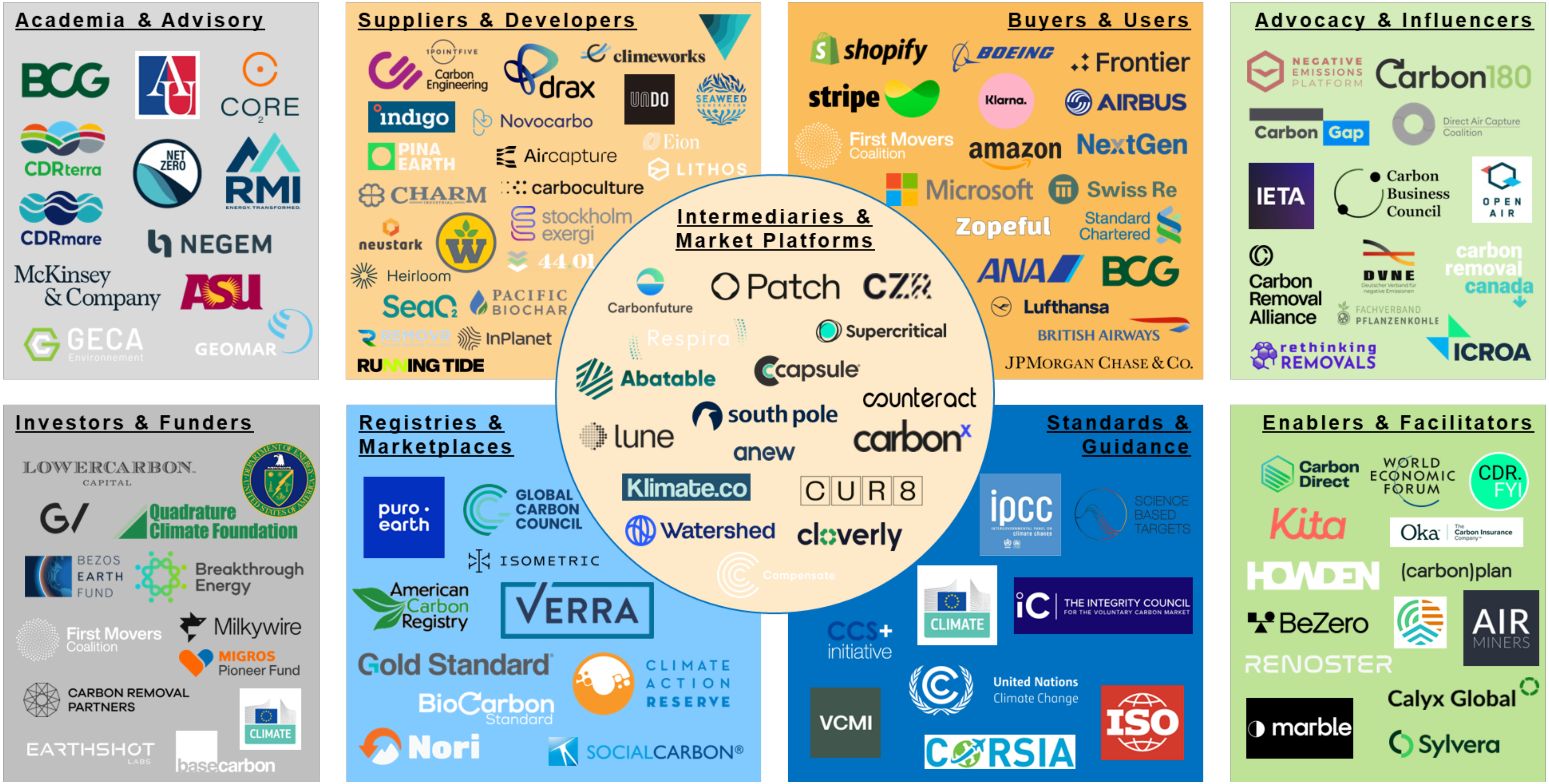
A provisional map of this emergent CDR ecosystem is set out below (Figure 2-4).

Note: the figure attempts to illustrate the range and diversity of the emerging actors and activities in the CDR space; it does not aim to promote specific activities or organisations and is not exhaustive. The focus is on carbon market participants that are exclusively deploying CDR, making significant CDR deals or are influential actors in the CDR policy and finance fields.

Per above (Box 2-1), both government and corporate climate action look to be important in maintaining CDR momentum towards future development and deployment. Key actions driving further evolution of each are outlined below, covering:

- The status of CDR credit procurement programmes
- The certification methodologies and protocols through CDR credits could be originated
- Other policy developments influencing the CDR landscape for both private and public sector actors.

Figure 2-4 Illustrative outline of the emergent global CDR ecosystem



Note: the outline is illustrative and not exhaustive. Clusters are indicative of the activities undertaken by the organisations per information on their websites. The authors accept no responsibility for omissions or errors in clustering.

2.3.1 Corporate commitments and action

The private sector is the dominant driver of CDR momentum at the time of writing. Action by a select but growing group of corporate entities convinced of the merits of neutralising their emissions though CDR credit acquisition sits at the core of the CDR ecosystem (Box 1-1).

To date, forward purchase agreements for CDR credits by such entities exceeds 5.5 million tCO_2 with a combined value of US$ 2.8 billion.[14] Of these, around 220,000 tCO_2 have been delivered, equating to just under 4% of the contracted amounts.[14] As indicated below, Microsoft, BCG, Shopify and the various buyers' clubs (Frontier, NextGen) remain major sources of diverse CDR demand (Table 2-1).

The willingness-to-pay for CDR credits is also robust, with prices reaching up to US$ 1,750/tCO_2 for ocean alkalinity enhancement projects, US$ 886-2054/tCO_2 for DACS, US$ 435/tCO_2 for ERW, and US$ 200/tCO_2 for biochar (Stripe 2021; Allied Offsets 2023). In May 2023, a US$ 53 million deal announced between Frontier and Charm Industrial for U.S. bio-oil injection derived credits suggests a price equivalent to US$ 473/tCO_2 (for 112,000 tCO_2).

According to analysis on www.CDR.fyi, in 2024, 80% of purchasers are budgeting over US$100 per tonne for durable CDR.[14]

In respect of market outlooks, highlights include:

- **Microsoft**. The firm's commitment to a 2030 carbon negative target has made it by far the largest global contractor for CDR offtake, standing at more than 3 $MtCO_2$ at the time of writing (Table 2-1). Company reports indicate that, at the end of 2022, the firm had retired over 514,000 tCO_2 of CDR credits and anticipates future annual demand in 2030 to be ~5 $MtCO_2$ CDR in line with its carbon negative goal (Microsoft 2023).
- **Frontier** (buyer's club). Reports that the club holds over US$ 1billion, primarily for offtake contracts, of which only US$156 million has been committed to date.[15]
- **NextGen** (buyer's club). Reports that it is committed to purchasing 1 $MtCO_2$ of CDR by 2025 at a target price of US$ 200/tCO_2.[16]
- **First Movers Coalition**. A public-private a consortium of 13 governments[17] and almost 100 companies. Among other actions, members can commit to contract for durable and scalable net CDR, either for more than 50,000 tCO_2 or more than US$ 25 million procurement by the end of 2030.

[14] www.CDR.fyi (January 2024); www.CDR.fyi 2024+ Market Outlook Summary Report.
[15] Stripe, Alphabet, Shopify, Meta, McKinsey & Co, H&M, JP Morgan Chase, Autodesk, Workday. Activity details from https://frontierclimate.com/progress (accessed January 2024)
[16] South Pole, Mitsubishi, BCG, LGT, Mitsui O.S.K Line, Swiss Re, UBS. From https://www.nextgencdr.com/ (accessed January 2024)
[17] Australia, Canada, Norway, Denmark, Sweden, Singapore, Germany, Italy, India, Japan, UAE, UK, U.S.

- **Shopify, BCG** and **JP Morgan Chase**. Despite being members of the buyer's clubs mentioned above, are all individually maintaining strong CDR supply portfolios (Table 2-1).

Table 2-1 Top 15 CDR buyers (at January 2024)

Buyer	Contracted CDR (tCO_2)	Type	Example suppliers(s)
Microsoft	3,260,503	BC, Min, DAC, BECCS, EW, Bio-oil	Orsted, Climeworks, Heirloom, Exomad Green, UNDO, Charm Industrial, Lithos, Carbonfex, Running Tide, Mash Makes etc
Airbus	400,000	DAC	1PointFive
Frontier	250,000-360,000*	DAC, Bio-oil, EW, EC mCDR, Biomass burial	Charm Industrial, Lithos, Climeworks, Heirloom, Carbon Capture, Cella, Deep Vault, Mati, Rewind, Alkali Earth, Vaulted Deep
NextGen	193,125	BECCS, BC, DAC	CarboCulture, 1PointFive, Summit Carbon
BCG	121,565	DAC, BC	1PointFive, Climeworks, Carbon Capture, Netzero, Oregon Biochar
Shopify	87,223	BC, DAC, EW, OAE, Biomass burial	Bussme Energy, Lithos, Heirloom, Planetary, Charm Industrial, Vaulted Deep
JP Morgan Chase	63,822	BECCS, DAC, Bio-oil, BC	CO280, Climeworks, Charm Industrial, Glanris
Google	62,583		(undisclosed)
Boeing	62,000	EC mCDR,	Equatic
Climate Cent Foundation	51,300	BECCS, Min	Neustark, Regionalworke AG Baden
UBS	39,500	DAC, Min	Climeworks, Neustark
Swiss Re	29,092	BC, DAC,	Oregon Biochar, Exomad, CarbonFex, Novocarbo, Freres Biochar Climeworks
TD Securities	27,500	DAC	1PointFive
Klarna	21,602	DAC, EW, BC, BECCS, Biomass burial	Octavia, SeaO2, Mission Zero, Silicate, Takachar, Inplanet, InerEarth, Heirloom, Husk
Nippon Airways	20,000	DACS	1PointFive

Source: www.cdr.fyi (accessed January 2024) and other sources.
Notes: BC = biochar; Min = Mineralisation; EC mCDR = Electrochemical ocean CO_2 removal.

Private sector certification

Conventional CDR has long been a key part of the VCM, and more than 50 crediting methodologies and protocols for agriculture, forestry and other land use (AFOLU) activities exist across a range of ICPs (see, McDonald et al. 2021; Mercer and Burke 2023; van Baren et al. 2023). According to Ecosystem Marketplace (2023; 2024), credits from these activity types accounted for around 45% of the 254 $MtCO_2$ of transacted volumes in the VCM in 2022, and 33% of the 111 $MtCO_2$ of 2023 market volumes.

The VCM ecosystem for novel CDR methods is also evolving rapidly. From virtually nothing three years ago, ICPs and other developers on the supply-side of the VCM, especially CDR specialists, have responded to growing corporate demand by developing a range of new MRV standards. At the time of writing, around 20 methodologies covering a diverse range of novel CDR methods have been published, with several more under consultation or preparation (Table 2-2). Several methodologies include a range of sub-modules applicable to different configurations (e.g. Verra's CCS methodology and Isometric's DAC, bio-oil and OAE methodologies).

Table 2-2 ICP methodologies for novel CDR in the voluntary carbon market

CDR method	Meths#	ICP/Developer	Dates of publication
BECCS	7	Puro.earth; ACR;* Verra/VCS (CCS+);* Global Carbon Council;* Isometric; Drax/Stockholm Exergi; Gold Standard;	Jan-2021 → Jun-2024 (ACR v1.0 dated Apr-2015)
DACS + geostorage	5	Puro.earth; ACR;* Verra/VCS (CCS+);* Global Carbon Council;* Isometric	Jan-2021 → Dec-2023
DACS + mineral storage	1	CarbFix/Climeworks/DNV	Jun-2022
Enhanced weathering**	3	Puro.earth**; Verra/VCS**; Isometric	Mar-2023 → Apr-2024
Biochar	2	Puro.earth; Verra/VCS	Jan-2022 → Jul-2023
Bio-oil storage	2	Isometric; Carbon Direct	Aug-2022 → Dec-2023
Biomass burial	2	Puro.earth; Isometric	Nov-2023 → Dec-2023
Biomass sinking	1	Social Carbon	May-2023
Ocean alkalinity enhancement (from coastal outfalls)	1	Isometric	May-2024

Source: authors analysis. Notes: Some DACS and BECCS methodologies are combined in a single protocol. *Includes fossil CCS. **Idea note, proposal, under preparation or under consultation.

2.3.2 Government action and support

As signatory Parties to the Paris Agreement and custodians of Paris-aligned climate plans in NDCs and Long-Term Low Emission Development Strategy (LT-LEDS), governments must look to lead on CDR development. Action by government can bring to the fore the deep pool of government resources and can help to build public trust in novel CDR methods.

Ongoing political and funding support for CDR at the time of writing includes:

- **United States (U.S.).** the Inflation Reduction Act of 2022 (IRA) and updated 45Q tax credits, which seeks to mobilise almost US$370 billion for carbon management of which around €2 billion is estimated encompass DACS and BECCS; 45Q now includes tax credits for DACS of US$180/t$CO_2$ stored; the Growing Carbon Solutions Act for conventional CDR; the 2023 CDR Purchase Pilot, which is has US$35 million for acquiring credits from, inter alia, DACS, biomass with carbon removal and storage (BiCRS) pathways; EW; the U.S. DOE DAC Prize etc.

- **Canada.** The Federal Carbon Management Strategy (acknowledges role of CDR and commits to consideration of specific incentives for CDR); Net Zero Accelerator is seeking to support DAC for feedstock provision.
- **Europe.** the EU Innovation Fund (continued support for large-scale carbon removal activities, e.g. Stockholm Exergi; Northern Lights CO_2 storage hub); **Sweden** (developing a national BECCS procurement programme); **Denmark** (tender processes for both CCS and negative emissions CCS [NECCS]); the **UK** (proposing business models for GGR and considering integration into the UK ETS).
- **Bilateral programmes**. Mechanisms under Article 6 of the Paris Agreement could provide an important conduit for CDR cooperation and trading between governments. In these respects, **Switzerland—**as probably the most advanced country with an Article 6 buying programme—has signed bilateral cooperative action agreements with a number of countries, including specific CCS and NETs arrangements (e.g. memoranda of understanding) with **Sweden, Iceland, the Netherlands** and **Norway**. The **UK** DAC competition offers up to GB£ 100 million for CDR activities.
- **Multilateral programmes.** For example, the 'Group of Negative Emitters' launched at COP28 by Denmark, Finland and Panama; the U.S. Carbon Management Challenge, which seeks to directly or indirectly maintain momentum for CCS and CDR; The First Movers Coalition (see above); the Mission Innovation 'CDR Launchpad'.

Public sector certification

Governments are also seeking to establish methodological standards that can be used to certify and credit CDR activities, albeit at a slower pace than the private sector.

At the **international level** under the UNFCCC, Decision 3/CMA.3 agreed in 2021 set down rules, modalities and procedures for the Article 6.4 mechanism (the so-called "RMPs").[18] Therein, a mandate was given to then newly-established Article 6.4 Supervisory Body (A6.4SB) to develop recommendations, by November 2022, on, inter alia, methodologies and activities involving removals, for consideration by the CMA.[19] The deadline was not met due to many demands on the A6.4SB, and so the mandate carried forward into 2023.

Subsequently, at the 9th meeting of the A6.4SB in November 2023, a draft recommendation on removals was prepared to put forward to the CMA at COP28. The recommendation covered a range of areas that are critical to the implementation of high-quality removals crediting including, inter alia (see also Section 4.2):

[18] Article 6.4 is a crediting mechanism established by the Paris Agreement to be operated by the UN and governed by parties to the Paris Agreement. The Article 6.4 mechanism is overseen by a Supervisory Body with the support the UNFCCC secretariat. The supreme governing body of the Article 6.4 Mechanism is the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement ('the CMA').

[19] Decision 3/CMA.3, paragraph 6(c) calls for recommendations on removals to take account of appropriate monitoring, reporting, accounting for removals and crediting periods, addressing reversals, avoidance of leakage, and avoidance of other negative environmental and social impacts.

- **Monitoring**. Specifying that project operators would need to apply a range of techniques (e.g. field measurements, remote sensing, measurement through instrumentation, or modelling, in combination as necessary).
- **Avoidance of leakage and other negative environmental and social impacts.**
- **Post-crediting period monitoring, reporting and remediation of reversals**. To oblige developers to continue monitoring in order to ensure that the residual risk of the reversal of removals for which credits were issued is negligible and/or that potential future carbon reversals are addressed in full, even after the activity is no longer being credited.
- **Addressing reversals through risk assessment**. A proposal to develop a non-permanence risk assessment tool, and to use buffer accounts that withhold a portion of issued credits to be called upon to remediate any future carbon reversal.
- **Actions post reversal**. Specifying procedures and requirements in the event of a carbon reversal, including reporting, corrective actions, preventative actions, reinstatement of crediting etc.

However, at COP28 in December 2023 Parties failed to gain consensus on the A6.4SB's draft recommendation on removals nor on methodologies. Consequently, proposals for new UNFCCC government-backed crediting methodologies for CDR under the Paris Agreement should be expected before 2025 at the earliest.

Canada is currently developing its first federal DACS protocol for the GHG Offset Program, credits from which can be used in the federal Output-Based Pricing System or the VCM.

In **Europe**, the EU is also seeking to implement governmental oversight of voluntary standards for certifying CDR. In 2022 the European Commission (EC) put forward a proposal for a carbon removals certification framework (CRCF; now, carbon removals and carbon farming),[20] which looks to establish an overarching "QU.A.L.ITY"[21] framework for the CDR activity certification occurring in the VCM, covering both conventional and novel CDR and C storage in products. Revisions by the European Parliament have now expanded the scope of the finalised regulation to include both CDR and emission reduction activities in the EU agricultural sector.[22]

The EC has indicated that to demonstrate that carbon removals comply with the EU quality criteria, operators of CDR activities will need to apply to a public or private certification scheme (i.e. ICP) that has been recognised or approved by the Commission. The plan is for the activities of CDR operators to be regularly verified and certified by independent certification bodies that will check compliance with EU rules. The legal draft also implies that the application of EU quality criteria to scheme operators would be implemented voluntarily.

[20] Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals. COM(2022) 672 final. 30 November 2022.
[21] **QU**antification, **A**dditionality, **L**ong-term storage, sustainabil**ITY**
[22] European Parliament, Report - A9-0329/2023. As of March 2024, the final text has been agreed by the EC, Parliament and European Council.

The EC also states that, with the support of an Expert Group, it will develop tailored certification methodologies for the different types of carbon removal activities. As of June 2024, the 70+ public and private sector members appointed to the CDR Expert Group have participated in four meetings since March 2023. But so far, no methodological frameworks have been put forward for consideration.

The **UK Government** has also put forward its views on GGR business models, recently stating its intention to: [23]

> "…define the methodologies that GGR projects supported under the business model will need to meet rather than endorse one, or multiple, third party methodologies. Government methodologies to support the business model will reflect our MRV policy principles and ensure consistency across the wider range existing HMG standards and policies…"[24]

2.4 The challenges for CDR policy

Notwithstanding the opportunities for CDR development, progress with CDR-based climate action also faces various technical and political challenges.

2.4.1 Technical

On the technical front, not all CDR is created equal. Certain methods are generally well-understood in respect of known risks and limitations (e.g. forestation; geological CO_2 storage), especially in respect of durability, costs, environmental risks and public acceptance (Table 3-2; Table 3-3). On the other hand, more novel CDR methods still pose fundamental technical questions and challenges, with uncertainty persisting over, inter alia, their ability to remove CO_2 (efficacy), to do so on a net basis consideration overall system inputs and outputs (efficiency; boundary-setting), the possibilities to accurately measure the net CO_2 removal effect (monitoring viability; baselines) and clarity regarding the fate and behaviour of captured C, CO_2 or related byproducts (monitoring, durability/permanence of storage; Table 3-4; Table 3-5).

As such, it remains unclear whether all types of proposed CDR methods will be able to contribute towards climate mitigation, or whether they can do so at the pace and scale aligned with net zero targets. Scenarios and IAMs informing the IPCC's latest CDR estimates are constrained by a lack of knowledge and foundational science on the potential of a wide range of novel CDR methods, with analyses applied in the AR6 principally relying on forestation (afforestation/reforestation), BECCS, and a small amount of DACS. Smith et al. (2023) note that work is underway to incorporate a wider array of CDR methods in IAMs, which could

[23] *Greenhouse Gas Removals: Update on the design of the Greenhouse Gas Removals (GGR) Business Model and Power Bioenergy with Carbon Capture and Storage (Power BECCS) Business Model*. DESNZ, December 2023.

[24] The UK DESNZ GGR MRV Principles are: Accurate, Consistent, Continuous Improvement, Environmental Safeguards, Simplicity, Parity, Transparent. Source: *Engineered Greenhouse Gas Removals: Government response to the consultation on a GGR Business Model*. DESNZ, June 2023.

produce lower mitigation cost estimates for scenarios involving CDR. Such integrated assessments could also help to reveal further information about the cross-sectoral benefits and GHG effects that could potentially arise from deploying of a portfolio of CDR methods.

On this basis, CDR methods are a complementary measure to solve climate change rather than a panacea or silver bullet. Importantly, all scenarios underpinning the IPCC's AR6 also include rapid, deep, and in most cases immediate GHG emission reductions in all sectors to achieve Paris-aligned temperature goals. Some IPCC scenarios also achieve the goal without relying on significant amounts of human-induced CDR (e.g. the P1 scenario drawing from Grubler et al. 2018).

Gaining a better understanding of the various CDR methods and approaches to their MRV is essential to building their credibility as climate mitigation solutions that can effectively contribute towards the Paris Agreement goals. Such progress is vital to support sound governance and policymaking. As noted by the IPCC in AR6:

> "CDR governance and policymaking are expected to focus on responsibly incentivising RD&D and targeted deployment, building on both technical and governance experience with already widely practised CDR methods like afforestation/reforestation…learning from two decades of slow-moving CCS deployment… [and] …for some less well-understood methods and implementation options, such as ocean alkalinisation or enhanced weathering, investment in RD&D can help in understanding the risks, rewards, and uncertainties of deployment." (Babiker et al.2022; p.1277).

2.4.2 Political

On the political front, CDR also faces challenges, primarily because many consider it to pose moral hazards.

Some observers assert that the promise of the future availability of CDR acts as an excuse to put-off emission reductions today. This phenomenon has been referred to as mitigation obstruction (Fuss et al. 2018) or mitigation deterrence (McLaren et al. 2019). On this basis, allowing C removals to directly offset fossil C emissions has been broadly criticised because of the risks of deterring, or at least deferring, decisions and actions to reduce GHG emissions. Nonetheless, the very basis of net zero seems entirely predicated on such an 'offsetting' arrangement.

Other observers have also contested whether CDR—especially those methods relying on storage in less durable biological C reservoirs in the short carbon cycle—can be directly equated with contemporaneous fossil C emissions (e.g. Carton et al. 2021). Among others, concerns centre on the risks posed by offsetting *permanent* CO_2 emissions from fossil fuel combustion by *impermanent* CO_2 removals—a problem that is referred to as 'false equivalency'.

Separation of targets between emission reductions and removals has been proposed as a means to address such moral hazard concerns; that is, the establishment of specific new targets solely for removals that are independent of emission reduction goals (McLaren et al. 2019; Geden and Schenuit 2020; Jeffrey et al. 2020; Zakkour et al. 2021). Proponents assert that this will provide greater transparency regarding how climate neutrality targets are intended to be met, while removing the potential for interactions with emission reduction-based policies.

Over recent years, a number of groups have lobbied for separate targets within EU climate policy.[25] However, target separation potentially raises new questions about who should pay for CDR (if the target cannot be directly devolved to economic actors that are responsible generating GHG emissions)? Thus, additional questions include: how, can, or why should emitters pay when they cannot access offsetting claims? which entities other than emitters could pay for or perform CDR? what accounting and claims could be allowed against removal actions? These important questions are not the main focus of this report but remain germane to the integration of CDR into climate policy (Section 4 provides some views on the accounting and claims).

Another mooted policy prescription to address false equivalency is idea of “like-for-like” balancing. This involves durable net zero strategies requiring the matching of anthropogenic greenhouse gas sources and sinks in terms of both origin (biogenic versus geological) and gas lifetime (Allen et al. 2022).

Moreover, at the time of writing the coupling of the strong moral concerns among some stakeholders to the CDR ‘boom’ underway among others poses something of a difficult nexus for policymaking. The attention has precipitated an increasingly fractious and polarising debate and scrutiny of CDR related policy matters. For instance, the publication in 2023 of a CDR Information Note by the UNFCCC Secretariat caused widespread concern from stakeholders for being both too critical (primarily of engineered CDR, but also in respect of over-relying on CDR more generally) and too supportive (mainly in relation to nature-based or biological CDR). The subsequent calls for inputs on the A6.4SB CDR work programme attracted 378 responses from non-governmental organisations (both positive and negative) but only eight from government.[26] The sheer volume of input requires time and effort to parse and synthesize, which also hampers decision-making and fosters procrastination.

Context also matters for CDR policymaking. The calls for target separation notwithstanding, a growing body of literature is exploring pathways through which to integrate CDR into mainstream climate mitigation policy, and especially carbon pricing instruments such as emissions trading systems (ETSs; e.g. for example, La Hoz Theuer et al. 2021; Rickels et al. 2021; Zakkour et al. 2022; Edenhofer et al., 2023; Bognar et al. 2023). However, the exact nature of the challenge remains somewhat under-explored and unaddressed. But matters typically considered for CDR certification/crediting—such as boundaries, leakage, additionality and permanence—pose differences for those jurisdictions with ambitious and stringent climate PAMs (e.g. national carbon pricing) compared to those without. Furthermore, contrary to what

[25] e.g Bellona Europe; Net Zero Asset Owners Alliance (NZAOA); Carbon Market Watch (and over 40 others)
[26] see: A6.4-SB007-AA-A13 – Information note: Compilation of the public inputs on removal activities under the Article 6.4 mechanism

seems to be widespread thinking, national level net zero accounting is not a simple case of governments acquiring CDR credits and accounting for them as offsets against national GHG emissions like other organisations can in the VCM (Box 1-1). Per the discussion below (Section 4.3), the accounting methods do not work in entirely the same way.

Mindful of these challenges, the remaining sections consider the technical features of different CDR methods (Section 3) and the approaches towards the MRV and accounting of their related GHG emissions and removals (Section 4).

3 Characterizing and assessing CDR methods

The following section provides a characterisation and high-level assessment of the key features of various CDR methods, and how these may impact upon their potential to meaningfully contribute towards climate change mitigation. In the context of latter, that is to be deployed at a pace and scale broadly aligned with the Paris Agreement global net zero goal in the second half of this century.

The primary purpose is to offer indicative signposts as to the main opportunities and more challenging areas facing the deployment and scale-up of a range of CDR methods.

3.1 Methodology

The evaluation methodology is applied in three steps: clustering, criteria development, and evaluation.

3.1.1 Step 1 – Clustering of CDR methods

The first stage of the evaluation was to condense the number of CDR methods reviewed (around 18; Section 2.1) into a smaller set through clustering and categorization. The process reduces the results into a manageable set of findings that can assist in communicating the broad characteristics of CDR and the different choices and trade-offs they may present.

Four broad categories of CDR methods were identified, primarily clustered according to similarities in the C storage medium (as noted previously; Section 2.1). The type of C sink and reservoirs enhanced by the CDR method (i.e. the terrestrial C pool within which captured C is stored) is considered here to be the primary factor affecting a methods' capacity to meaningfully contribute towards climate mitigation (e.g. availability, scalability, durability, acceptability).

The C capture technique is also an important factor for various reasons including the availability and sustainability of materials used and other inputs, their cost and process efficacy. Indeed, some scholars have used the capture method as the primary basis for assessing CDR. For example, Lenton (2014) indicates a preference to depart from previous CDR categorisations of "biological, chemical and physical approaches, or land and ocean-based approaches" towards the following grouping:

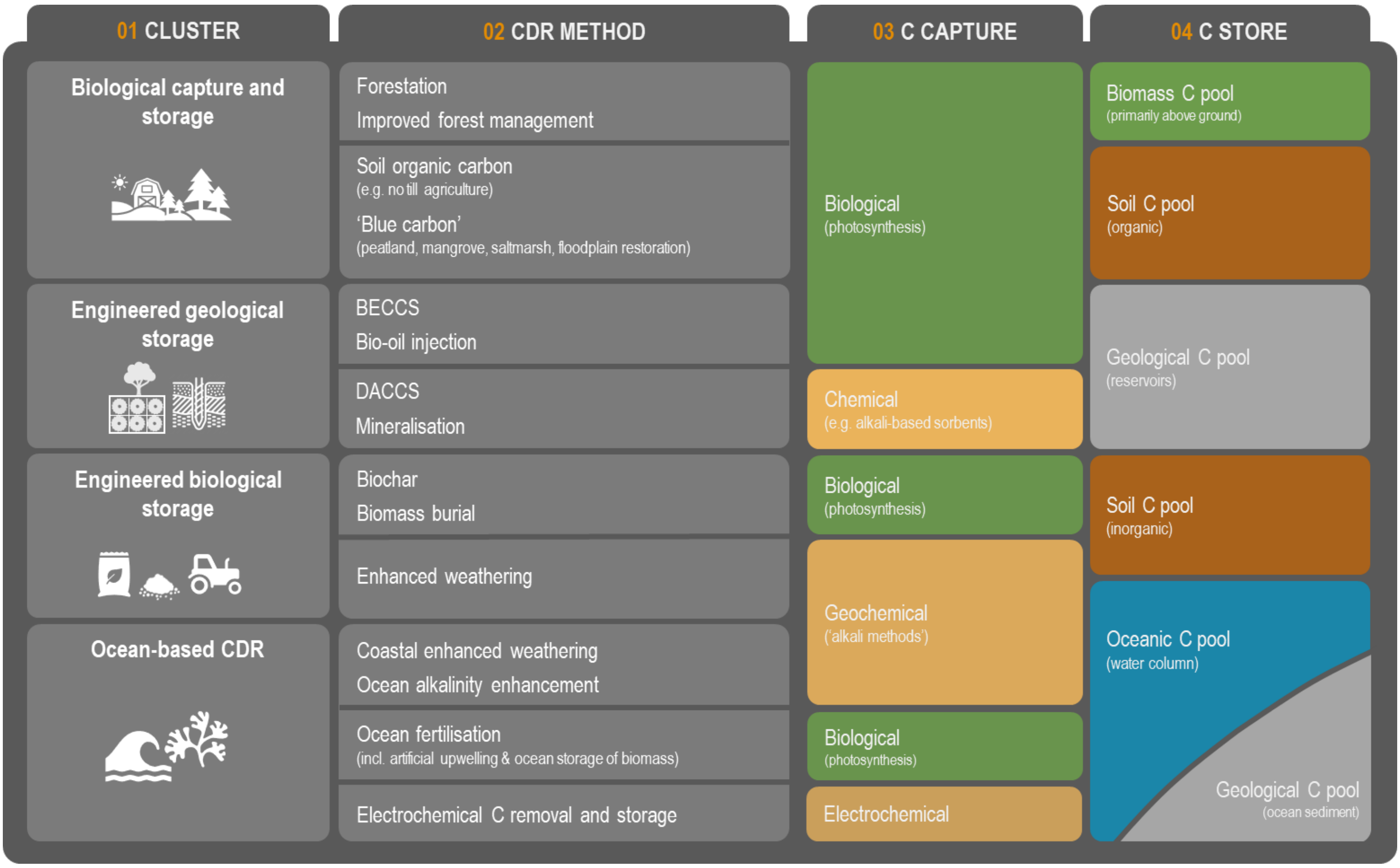
1. Plant-based CDR (forestation, forest management, biomass burial, biochar, BECCS)
2. Algal-based CDR (algal BECCS; ocean fertilisation);

3. Alkalinity-based CDR (chemical sorbents used for DACS,[27] enhanced weathering, ocean alkalinity enhancement), etc.

Lenton's goal was to characterise rate limiting steps for each CDR method so as to arrive at estimates of the total technical potential of each in terms of net atmospheric CO_2 flux. The assessment here, on the other hand, seeks to take account of a wider set of non-technical factors that could impact upon deployment, encompassing important aspects relating primarily to storage, but also to capture as a secondary basis for clustering (see Figure 3-1).

These observations notwithstanding, clustering and categorisation based on the main C storage medium is also not perfect, with several methods involving overlaps. In the case of EW (or enhanced rock weathering), for example, C can be stored in soil, freshwater systems, the oceanic water column, and, ultimately, the geological C pool (following synthesis of dissolved inorganic carbon by marine organisms). In the case of mCDR methods, all result in a blend of storage of C in the oceanic water column as well as ongoing stock transfers to the geologic C pool.

Figure 3-1 Taxonomic relationships used to cluster CDR methods



Source: authors own interpretation

[27] Which are also used to capture CO_2 in BECCS.

There are other notable limitations in the taxonomic categorisation shown in Figure 3-1. For example, known combinations of C capture and storage not covered in the assessment include: biomass burial in salt caverns (biological capture with geological C storage),[28] biomass sinking in lacustrine sediments (non-oceanic geological C storage in lake sediments),[29] and biogenic C storage in the technosphere (e.g. in building elements made from harvested wood products (HWP) or captured biogenic CO_2 mineralised into recycled concrete etc.).[30] In the case of the latter, although product storage is partially included in the review (see Annex A), it is excluded from the evaluation due to resource constraints uncertainty of acceptable levels of durability (especially HWP).

3.1.2 Step 2 – Evaluation criteria

The clusters of CDR methods developed in Step 1 were assessed against key criteria impacting upon their feasibility to meaningfully mitigate climate change. In simple terms, the evaluation seeks to heuristically answer, through a literature review and other information sources, the following key questions in relation to each CDR cluster:

- Whether it works? (in delivering a net GHG removal effect)
- What it needs to work effectively? What factors impact upon its effectiveness? (e.g. to deliver a net GHG removal rather than net GHG emissions effect)
- How long does it work for? (i.e. how long could the GHG removal effect last for?)
- Does it create any other negative environmental or social impacts?
- Can it be done at significant scale?
- How long does it take to work? How quickly can it be deployed and scaled?
- Are there other important factors to take into account? (e.g. social acceptability, legal aspects, costs, time needed to function)

These basic questions are re-framed as assessment criteria below (Table 3-1). The assessment here does not take account of “MRV-ability” since this aspect is covered more comprehensively in Section 4. However, there is a close connection between technical characteristics and MRV-ability, which are discussed below.

Drawing upon the questions above, a review of selected previous studies was undertaken to gain insight on how others had sought to assess the feasibility of CDR. Findings from the research were used to develop, refine and validate the evaluation criteria shown. Investigations indicate that various attempts have been made to assess the scale-up potential and feasibility of CDR, which have been applied at varying levels of granularity and for various purposes, including by Lenton (2014), Nemet et al., (2018), Oxfam (2020), Fridahl et al. (2020), Bey et al. (2021) and Förster et al. (2022). These are discussed briefly below.

[28] Isometric has a certification methodology for this technique (Biomass Geological Storage v1.0)
[29] As being explored by Rewind. Social Carbon has a certification methodology for this technique (Methodology for the treatment of Harmful Algae Blooms (SCM007))
[30] Neustark is using a technique involving biogenic treatment of recycled concrete and has developed a certification methodology with Gold Standard for this technique (Methodology: Carbon sequestration through accelerated carbonation of concrete aggregate).

Table 3-1 Evaluation criteria applied to CDR clusters

Criterion	Description	Contexts
01 Efficacy	Proven capacity to remove C from the atmosphere (including at a rate useful to meeting near-term climate mitigation goals i.e. to 2050 or shortly thereafter)	Relates to the current level of understanding of basic, foundational, science. Inferred from the extent to which the method has been demonstrated in a working prototype or at field-scale (e.g. TRL 6 or higher), with field experiments showing discernible, measurable, CDR effects.
02 Efficiency	Ability to remove more C than is emitted (e.g. extent of unabated fossil energy consumption needed to deliver the removal effect).	Relates primarily to the full chain, lifecycle GHG emissions of the given CDR method. For many CDR methods, this is intimately linked the materials and energy used and the availability of decarbonised energy supply. Challenging to gauge, but at present can be considered to be finite and non-abundant. Also poses a paradox and significant questions over trade-offs: increasing the availability of decarbonised energy can reduce the need for CDR to achieve climate goals. The balancing point in these respects is presently unclear. Current IAMs heavily rely on BECCS, which delivers both decarbonised energy and CDR. As noted above, IAMs are seemingly not at a stage where they can fully address the trade-offs (Section 2.4).
03 Durability	Ability to store C for a length to time that is meaningful in respect of climate mitigation.	Relates to how long C can and should be stored for in the receiving media. Open discussions remain about what should constitute high durability (permanent) CDR. Present views on the matter are considered in the context of methodologies and MRV below (Section 4.2.5). Information presented there is used to inform the evaluation.
04 Sustainability	Ability to remove carbon with no or limited negative impacts upon the environment and society.	Relates to factors such as the abundance of, and impacts relating to, the sourcing and processing of input materials, energy, water etc. (e.g. source of biomass, source of clean energy, sufficient water availability, acceptable air emissions). Also, the amount of waste and wastewater production, including hazardous waste. Challenging to gauge. Most CDR methods pose the risk of some negative environmental and/or social risks and side effects, leading to trade-offs. Co-benefits can also be a feature (e.g. soil fertility, soil amelioration, biodiversity)
05 Scalability	Ability for deployment to expand to levels anticipated to be needed to meet near-term climate goals (e.g. to 2050).	Relates to availability and accessibility of relevant C storage media and of input materials needed in the CDR process (excluding socio-economic factors, per below) Challenging to gauge. Around 0.5 to 1.0 Gt by 2050 would seem like a meaningful threshold for scalability of a given cluster.
06 Availability / Timeliness	Ability to be deployed at scale in a relevant timeframe, taking account of other non-technical factors.	Societal and economic concerns could impede deployment and scale-up (e.g. cost, social license, legal impediments and barriers). These factors will reduce the rate at which the CDR might become available for it to upscale.

Note: TRL 6 = demonstrated in relevant environment

As previously noted, Lenton (2014) was primarily interested in CDR technical potential based on a straightforward input~output view of: (a) the flux of CO_2 removal that can be achieved at a given time; and; (b) whether there is leakage of CO_2 from the storage reservoirs back to the atmosphere, and if so, at what rate. In determining (a), Lenton (2014) invariably took account of key secondary rate-limiting factors covering (sic): (1) a supply of some limiting resource(s) to capture CO_2; (2) a yield of carbon per unit input of limiting resource; and (3) the conversion efficiency of that carbon to long-lived storage, including a supply of resource(s) to achieve that capture. Lenton (2014) also took the view that a scientific perspective on potential comes "before also thinking about the engineering, the costs and the social acceptability of CDR technologies." (Lenton 2014, p. 54). Conversely, more recent literature suggests that CDR feasibility assessments should not "gloss over" significant social barriers (Buck 2016; Bellamy 2018) and should also take account of biodiversity impacts including from a "threat identification" perspective (Dooley et al. 2020). Hence, a wider scope is adopted in the evaluation criteria.

Nemet et al. (2018) undertook a review of the scholarly literature on innovation and upscaling of negative emission technologies (NETs, equivalent to CDR). Their findings note that the ultimate measure of success for a particular technology is adoption, surmised as a function of its relative advantage—in terms of cost, efficiency, quality, environmental impact, etc.—and its alignment with consumer preferences (Rogers 2003; Fouquet 2010).

Oxfam (2020) made a high-level heuristic assessment of CDR with a view to providing information to private funders and investors. In addition to reviewing methodological aspects (additionality), the assessment took account of speed, permanence, social and environmental obstacles, co-benefits, price and maturity. The assessment applied a low/medium/high/very high scoring approach and a 'traffic light' system to present the results graphically (Oxfam 2020, p. 6).

Fridahl et al. (2020) developed prospective "indicators for a negative emissions climate stabilisation index". They propose five categories—effectiveness, efficiency, scale, risk, and synergies—underpinned by 21 individual indicators that aim to capture both positive and negative features. The authors note that the value of NETs is very site-specific, and results would likely vary by location (Fridahl et al. 2020). They also do not propose any weightings between categories or criteria, but suggest that this is an important feature to consider.

Bey et al. (2021), in reviewing a wide range of CDR methods, assessed, inter alia, solution readiness, removal potential, practical challenges, co-benefits/negative externalities and permanence. The purpose of their study was to characterise rather than evaluate CDR methods.

Förster et al. (2022) undertook a multi-disciplinary and comprehensive approach to creating a national CDR feasibility assessment framework, taking account of environmental, technological, economic, social, institutional, and systemic implications of upscaling CDR options. They applied their approach to Germany working with more than 60 indicators across each of their five dimensions and applying a +/- across five ranks ('likely hurdle' to likely 'no hurdle') and applied traffic light scoring system for each indicator. The scores were informed by expert opinion.

The factors described in previous feasibility assessments, characterisation studies and evaluations are all considered to be broadly consistent with the evaluation criteria outlined above (Table 3-1). Based on the reviewed literature, the detailed indicators proposed by both Fridahl et al. (2020) and Förster et al. (2022) were considered to offer useful sight lines for preparing a CDR assessment, and are aligned with the indicators proposed herein. In particular, the categories of Fridahl et al. (2020) of effectiveness, efficiency and scale are the same, while risk and synergies have overlaps with scalability, availability, durability and sustainability, albeit from a *positive* rather than *negative* attribute perspective. Furthermore, while extremely comprehensive, the number of indicators proposed by Fridahl et al. (2020) and Förster et al. (2022) also infer intricacy beyond the approach applied here. Fridahl et al. (2020) also note that some of the indicators lack standard data by which to assess performance, and that scoring and weightings for each indicator or category will likely involve participatory consultation and expert judgement. Such an assessment requires significant resourcing and is unclear whether the results would offer greater utility to decision-makers.

While there are clear constraints in trying to take a broad view on all the evaluation factors described above, useful signposts for policy trade-offs can be drawn from the fairly high-level assessment outlined below.

3.1.3 Step 3 – Characterizing and evaluating CDR method clusters

The assessment is presented by CDR cluster, applying the CDR criteria to each before bringing the results together into a summary graphic. This approach is considered to be most suitable given the primary interest in characterising the differences and commonalities between CDR methods, as opposed to seeking to make choices between one or other CDR method relative to a given criterion.

The evaluation is informed by a review of literature, legal status and other sources undertaken by the authors', and application of their expert judgement in assessing the relevant advantages, trade-offs and barriers faced by each CDR cluster. The information used to make the judgments is outlined in Annex A.

The findings for each criterion are gauged on a scale of approximately 1 to 10 (although no score is applied), and, unlike Fridahl et al. (2020), the framing of the criteria means that only positive attributes apply (so a higher ranking means comparative benefits, and vice versa). The results are presented with notes against each criterion below, and then displayed graphically using a spectrum analyser style 'light' gauge (Figure 3-2).

The evaluation is not an attempt to identify the most promising methods and to "pick winners; as most observers and experts will contest, a portfolio approach to CDR is essential to address location-specific factors and mitigate against risks of failure (e.g. see Carbon Brief 2016). Thus, the aim is rather to attempt to characterise and relatively assess a broad range of CDR clusters so as to cast more light on the possibilities for certain CDR types to innovate and deploy in coming years relative to others.

3.2 Results of evaluation by cluster

3.2.1 Biological capture and storage

Conventional CDR methods covered by this cluster encompass ‘natural carbon solutions’ or ‘nature-based solutions’ primarily involving tree-planting (increasing woody C stocks), forest management (to enhance the standing C stock and also dead organic matter etc) and soil management (to increase soil organic C (SOC) stocks).

Forestry

These CDR methods cover the following techniques:

- Afforestation involves the planting of tress on land previously never forested.
- Reforestation relates to the planting of trees on land that was previously forested but deforested at some point in recent history (under the Kyoto Protocol the deforested cut-off date was 31 December 1989, or at least 20 years prior to the start of the activity). Herein, afforestation and reforestation are referred to collectively as ‘forestation’.
- Other forestry activities that may deliver carbon removals include:
  - Improved forest management (IFM) (to increase C stocks in managed forests)
  - Agroforestry (planting of trees on agricultural land)

Converting land cover to forests will generally increase the size of the terrestrial C stock on a parcel of managed land compared to other, prior, uses (e.g. cropland, grassland, abandoned land).

Under IFM, changes in harvesting practices/intensity (extended harvest rotations; retention harvesting), actions to reduce disturbances and measures to increase biomass growth (thinning, drainage, new species) can lead to increased C stocks across all carbon pools (above ground biomass (AB), below ground biomass (BB), dead organic matter (DOM) and the soil (SO)). Such management actions are well established, but subject to variable implementation. Efficacy of IFM can also be cyclical, linked to growth and harvesting cycles (age class effects). Thus, the status of the individual forests (age structure; economic factors) strongly influences potential for forest C stocks to be increased by IFM.

Agroforestry takes place on cropland (and grassland) through low density (non-forest) planting.

Soils (including “blue carbon”)

Mineral soils may be managed so as to increase SOC. Management options include cover cropping, improved crop rotations (e.g. through inclusion of legumes and other nitrogen fixing crops), deep rooting crops, conversion from arable to grassland and other management of grazing land and grassland to increase SOC levels. (Bey et al. 2021)

In the case of heavy organic soils, peatland and wetland restoration seeks to slow and eventually reverse the degradation of organic soils. When drained, peatlands and wetlands release stored C and potentially other GHGs (Bey et al., 2021). Rewetting or restoring drained peatlands and wetlands predominantly involves blocking drainage channels to raise the water table. This process slows the release (oxidation) of SOC and allows the peatland to increase its C stock through plant growth and deposition (especially sphagnum sp.).

Modified management of coastal wetlands (salt marshes and flood plains) to reduce drainage and increase SOC falls within the scope of "blue carbon".

The summary evaluation of biological capture and storage is set out below (Table 3-2).

Table 3-2 Evaluation of biological capture and storage

Criterion	Characteristics
Efficacy	Forests remove CO_2 from the atmosphere by converting it to woody biomass via photosynthesis. Efficacy of measures to enhance SOC are less certain; mixed results from field trials.
Efficiency	Tree planting is the main form of human induced terrestrial CDR. Few inputs needed, and certain agriculture practices to enhance SOC can reduce fertiliser and vehicle (tractor) use, leading to emission reductions. Rewetting of organic soils can reduce CO_2 fluxes from soil but increase CH_4 emissions in the short term (1-10 years). Can offset the climate benefits of SOC enhancement (which can take longer)
Durability	Prone to human (deliberate) or natural (unintentional) rapid C reversal. Tree harvesting, changes in forest management, changes in agricultural practices, forest fires and pestilence all impact on storage durability, can all rapidly deplete the C stock and release CO_2 (flux) to the atmosphere. Ploughing can rapidly deplete SOC stocks.
Sustainability	Depends on approach taken. High co-benefits of mixed native forest planting. Fertiliser use on marginal lands and planting of non-native monocultures will significantly impair environmental benefits (requires safeguards)
Scalability	Forestation: high (5-10 $GtCO_2e$/yr) SOC and blue carbon: moderate/uncertain (2-5 $GtCO_2e$/yr)
Availability / Timeliness	Forests and SOC need time (20+ years plus) to reach new levels of enhanced C stock. Low cost. Land competition will restrict availability of land available for forestation.

3.2.2 Engineered geological storage

These methods involve the physical capture of CO_2 either directly from air (DACS) or from biogenic sources (BECCS) using chemical separation, its processing and injection into subsurface geological reservoirs for the purpose of long-term isolation from the atmosphere. One novel CDR method involves the production of ‘bio-oil’ and its injection into geological reservoirs for the purpose of long-term storage.

In the case of BECCS and bio-oil, capture of the CO_2 from air takes place through photosynthesis. Injection of the biogenic C into the geosphere leads to a stock transfer, reducing the amount of C in the shorter/faster biosphere-atmosphere cycle.

The summary evaluation of engineered geological storage is set out below (Table 3-3).

Table 3-3 Evaluation of engineered geological storage

Criterion	Features
Efficacy	CO_2 capture and storage proven in a number of settings and applications worldwide. BECCS: one or two facilities in operation capturing biogenic CO_2 for geostorage (e.g. Decatour, U.S.) DACS: largest operational plant is rated at 36,000 tCO_2/yr (in 2024)—the previous being 4,000 tCO_2/yr Bio oil: number of small-scale projects in the U.S. injecting corn-derived bio-oil into depleted oil and gas wells.
Efficiency	Significant energy requirement (electricity to drive fans etc; heat for solvent regeneration) Embodied carbon in materials, water and energy use can significantly impair effectiveness and efficiency. Location specific.
Durability	For storage in well selected, designed and managed geological reservoirs the fraction retained is very likely to exceed 99% over 100 years (90-99% probability) and is likely (66-90% probability) to exceed 99% over 1,000 years (IPCC 2005)
Sustainability	Water and materials use can result in environmental impacts. Waste production (spent sorbents) can present an environmental burden. Co-removal of air pollutants can be a benefit.
Scalability	Technical potential is significant (>10 $GtCO_2$/yr) Availability of storage sites is not considered to be a significant constraint (IPCC 2005; IPCC 2022). Flexibility offered by DACS could allow improved source-sink matching. Bio-oil injection likely to be limited by availability of oil and depleted wells in which to inject it.
Availability / Timeliness	Costs, public perception, project complexity, financing, transport and storage permitting etc can all be expected to impact upon deployment rates (drawing from analogues from fossil CCS progress).

3.2.3 Engineered biological storage

Biochar, and, to an extent, EW methods involve C storage as soil inorganic carbon (SIC). In the case of biomass burial, storage of organic carbon takes place within the soil, sealed inside an inert chamber.

- Biochar is produced from the combustion of organic material in a low or zero oxygen environment (pyrolysis). The resulting char is ground, bagged and sold as soil conditioner that is directly applied to soil (or as a construction filler). Pyrolyzed carbon (char) may remain in the soil in an inert state for significantly longer periods than organic C applied to soil in the form of, for example, fresh biomass or biogenic waste (manure, biosolids).
- EW methods involve the application of crushed rocks (e.g. calcium- and magnesium-rich silicate rocks mined from mafic and ultramafic sources such as basalt) to land (usually cropland) and coastal environments (e.g. beaches). The method relies on hydrolysis and carbonation reactions (chemical weathering) to break down the rocks

(i.e. the silicate-carbonate geochemical cycle). The 'weathering' reactions liberate base cations, which leads to the uptake of atmospheric CO_2 to form dissolved inorganic carbonate (primarily bicarbonate; HCO_3^-). Dissolved bicarbonate may leave the soil in drainage water and be stored and/or precipitated a long way from the original place of application. Dissolved inorganic carbon may also be sequestered through formation of soil carbonate minerals (pedogenic carbonate), but with stoichiometrically lower sequestration rates than for bicarbonate formation. Notably, conversion of bicarbonate to carbonate (e.g. through biosynthesis) liberates half of the stored C to CO_2.

- Biomass burial involves the interment of organic material (trees, other organic residues) in secure, non-perishable, chambers in the earth. The capture and preservation of biogenic material prevents its natural decomposition and the release (flux) of stored C back to the atmosphere as CO_2.

In the case of EW, run-off from EW-treated land will lead to C storage in water courses (e.g. carbonate precipitation in rivers and lakes), in the form of bicarbonate and carbonate ions the ocean (water column), and as calcium carbonate through biological synthesis (sediments).

The summary evaluation of engineered biological storage is set out below (Table 3-4).

Table 3-4 Evaluation of engineered biological storage

Criterion	Features
Efficacy	Techniques are conceptually feasible. Biochar: assuming sustainable and uncontaminated feedstocks, production can lead to a C stock transfer from organic C pool (e.g. woody biomass) to the SIC (soil inorganic C) pool. EW: not yet proven in field trials. Biomass burial: leads to a C stock transfer to inorganic/organic soil C pool.
Efficiency	Biochar: may lead to negative priming in some circumstances (breakdown of in situ SOC). Evidence is mixed and conditions driving priming effects are difficult to discern. EW. Energy footprint of mineral acquisition, commutation and application can impact upon effectiveness and efficiency. Biomass burial: cost and energy needs of internment remain unclear but may be high relative to the achieved CDR effect.
Durability	Biochar: IPCC (2019) provide indicative estimates of the 100-year retained fraction of 0.65-0.89, suggesting around 10 to 35% decay over 100 years. Experts estimate that, on average, 80% of biochar C persists in soil for >100 years (SLU 2023). EW: Conversion of bicarbonate to carbonate releases CO_2. In general terms, the characteristics of the soil inorganic carbon (SIC) pool is poorly understood, which hampers understanding of durability of these CDR methods. Biomass burial: natural analogues suggest potentially very long storage durations may be possible under specific conditions and circumstances.
Sustainability	Source materials (biomass quality, feedstock contaminants, mineral extraction) and processing (e.g. biochar conversion efficiency; biomass internment energy requirements) will significantly influence sustainability. Impacts on receiving environments remain largely untested (long term field trails yet to be concluded).
Scalability	Technical potential: moderate (~5+ $GtCO_2$/yr) Biomass burial: constrained by availability of sustainable biomass.
Availability / Timeliness	Biochar: requires scale up of significant new industry, and sufficient acceptance by farmers and other types of usage. Soil saturation levels may diminish potential. EW: yet to be proven at field scale. Biochar and biomass burial: constrained by availability of sustainable biomass.

3.2.4 Ocean-based CDR

A range of methods fall under the ambit of ocean-based CDR, including:

- Coastal Enhanced Weathering (CEW)
- Ocean alkalinity enhancement/alkalinisation (OAE)
- Electrochemical oceanic carbon removal and storage (direct removal of CO_2 and/or inorganic carbonates from seawater, and conversion to CO_2 for geological storage).
- Ocean fertilisation / Artificial upwelling (AU) / Ocean storage of biomass (OSB)

In most cases, the methods rely on modifying the partial pressure of CO_2 in seawater by changing pH through alkalinisation (i.e. charge balancing of base cations produced by weathering of dissolved CO_2 to form bicarbonate ions (HCO_3^-) and carbonate ions (CO_2^{-3})).

The removal of dissolved CO_2 through bicarbonate and carbonate formation leads to ingassing and the drawdown of atmospheric CO_2 into seawater through air-sea gas exchanges (i.e. removal of CO_2 from the atmosphere).

A pH change is achieved by either adding alkaline materials (which precipitates dissolved CO_2 into carbonates) or through removal of dissolved inorganic carbon (CO_2; bicarbonate; carbonate) from seawater. In the case of CEW and OAE, similar types of calcium- and magnesium-rich silicate materials that may be used for EW is deposited onto beaches or directly into the water column. In the case of ocean fertilization, dissolved CO_2 is removed from seawater by photosynthesis and fixed in biomass through growth and subsequent sinking. Electrochemical techniques also lead to the direct removal of dissolved inorganic carbon from seawater.

The summary evaluation of the ocean-CDR cluster is set out below (Table 3-5).

Table 3-5 Evaluation of mCDR

Criterion	Features
Efficacy	Techniques are conceptually feasible. Field trials for some methods have been implemented, but results remain uncertain. Efficacy of biomass sinking yet to proven.
Efficiency	Energy footprint of mineral acquisition, commutation, processing and application can impact upon effectiveness and efficiency of most techniques. Biomass sinking methods yet to be optimised. Decay of sunk biomass could lead to CH_4 formation.
Durability	Uncertain. Conversion of bicarbonate to calcium carbonate (e.g. through synthesis by marine organisms) leads to release of CO_2 Ability of sunk biomass to deliver durable storage remains somewhat untested.
Sustainability	Source materials (biomass quality, mineral extraction), processing and application (e.g. energy use) significantly influence sustainability of various mCDR methods. Risks to marine ecology from e.g. liberation or mobilisation of nutritive or toxic elements; deoxygenation risk (from fertilisation) etc
Scalability	Technical potential: very significant (e.g. some estimates of OAE at 100 $GtCO_2$) Other estimates are generally more modest (5-15 $GtCO_2$)
Availability / Timeliness	All methods face barriers, especially legality under marine protection treaties.

3.3 Comparative assessment

The assessment suggests that CDR methods involving biological and geological storage are the most mature, with relatively higher levels of proven efficacy. Nature-based biological CDR methods are the most efficient and sustainable, primarily because they do not require significant inputs of energy or materials to increase C capture or to anthropogenically enhance terrestrial C sinks and reservoirs. Engineered biological systems also score well for efficiency and sustainability, as they primarily rely on natural CO_2 capture processes. Geological CO_2 storage is seen to be the most durable in line with the geological C cycle (assuming short-term secure/stable physical trapping of CO_2 in geological reservoirs). Uncertainty over long-term performance of biochar and EW reduces the assessed durability for these solutions. Biological capture and storage and some mCDR are considered to present the greatest risk of C reversal in line with the potential for either natural and human induced events to rapidly deplete C stocks (e.g. forest fire, ocean circulation and upwelling). On the other hand, biological capture and storage offers the greatest sustainability co-benefits (e.g. conservation and habitat improvement).

Scalability and timeliness perhaps show the most interesting result. Most methods are considered to be scalable, consistent with estimated technical potentials shown above (see Figure 2-3). In respect of timeliness, all CDR methods face deployment challenges that hamper their ability to rapidly contribute towards climate mitigation by mid-century or shortly thereafter. In some cases it is the timeframe over which the removal effect functions (e.g. tree growth), while for others, the need for significant amounts of decarbonised energy (e.g. DACS) as well as other technical challenges can constrain deployment rates (e.g. CO_2 storage site identification, permitting and development). For mCDR, legal and public perception impediments are likely to present significant ongoing obstacles to widespread deployment.

Summary results of the technical evaluation are shown graphically below (Figure 3-2).

The generally lower scores and spread of scores shown across the final criterion of timeliness and availability reaffirms the widely held view that a portfolio of CDR will be essential to delivering meaningful climate mitigation over the near- to mid-term (see e.g. Carbon Brief 2016).

Figure 3-2 Summary results of CDR evaluation

Source: authors' own interpretations

4 MRV and accounting for CDR

Effective measurement, reporting and verification (MRV) lies at the core of sound climate policymaking (Box 1-2). This is especially true for CDR. The difficult negotiations on LULUCF accounting under the Kyoto Protocol and the protracted inclusion of both A/R and CCS in the CDM are testimony to the complex interface between actions to enhance terrestrial C sinks and the politics of climate rulemaking.

Variations in confidence regarding the efficacy, efficiency and durability of different CDR methods mean that climate policy, target-setting and incentives built around CDR is almost always contingent on implementing robust MRV. The slow progress of quantification methods and certification schemes, especially in the public sector, are a direct consequence of this tension. Sound MRV is essential to build confidence and trust.

In the offsetting framework that is inherent to net zero accounting—where the policy goal is to achieve a balance in emissions and removals to and from the atmosphere—equivalency of climate mitigation effectiveness is a de facto working assumption. In other words, there is an underlying cardinal principal that “a tonne is equal to a tonne” in respect of the MRV’d emissions, removals and other fluxes underpinning the scientific and political goal. Although simple in formulation, this disguises far more nuanced set of issues posed for CDR MRV and accounting. Indeed, as outlined previously, some observers question whether such an equivalency assumption should, at least in part, be consigned to history (Section 2.4.2). A more open discourse on these matters seems essential to help clarify and shape a more advanced dialogue around the means to effectively include CDR in climate PAMs.

Drawing on similar questions posed in the technical assessment in Section 3, robust MRV should address the following concerns about CDR methods at the level of a discrete activity:

- Does it deliver a net removal effect?
- Are the full range of GHG effects, including the gross and net CO_2 flux from the target C store, being identified and measured with sufficient confidence and accuracy?
- Are the attributed removals additional to what would have otherwise occurred?
- Is the removal effect permanent or temporary?

Problematically, not all CDR methods are created equal in these respects.

There are fundamental differences in the monitoring and measurement techniques that can be applied to different CDR methods. For some, the drawdown of CO_2 as a flow into reservoirs can be directly observed and measured, while for others a *net* CO_2 flux can only be inferred from measuring C stock changes over time. In the latter case, this usually involves discerning small net changes in very large C stocks, the measurements of which is subject to considerable error. Such errors may exceed the true level of net C stock change.

Challenges can also arise in isolating the specific GHG effect of a discrete intervention/activity relative to any naturally occurring background CO_2 flux for a given C sink or reservoir. The Managed Land Proxy applied in IPCC inventory methods is testimony to the challenges in partitioning such effects.[31] In other circumstances, uncertainty persists over whether an intervention/activity only creates a temporal shift in the cyclicity of the expected C flux rather than a sustainable long-term (permanent) C sink enhancement (e.g. age class effects in forest management). In some cases, the complex value chain involved in delivering a CDR effect cannot easily be tracked and the relevant emissions quantified, posing questions over efficacy, efficiency and the risk of leakage effects (e.g. the unsustainable harvesting of biomass).

Consequently, integrity concerns for climate policymaking are manifest: firstly, the effectiveness of climate mitigation PAMs will be compromised if they over-rely on flawed or incorrectly MRV'd CDR; second, incorrect MRV and mismatches in equivalency can create moral hazards: credits may be transacted to facilitate accounting and claims for purported climate benefits that that ultimately prove to be fleeting or incorrect. The various parties either performing such activities, issuing credits or making such claims may no longer be liable for any such errors or reversals, or may no longer be in existence.

Mindful of these issues, the remainder of this chapter considers CDR MRV from a number of perspectives. Firstly, the different facets of MRV as applied for different purposes are considered in more detail, building from Box 1-2. Second, the expectations for MRV related to specific CDR activities is assessed. Third, consideration is given to how MRV applied to different CDR activities can fit to the tracking and accounting systems that will ultimately guide whether and how progress is being made towards the Paris Agreement's goals. Finally, based on the discussion therein, an assessment is made of the MRV-ability of different CDR methods.

4.1 MRV approaches for CDR

4.1.1 MRV for GHG inventories

National GHG inventories

National Communications ("Nat Comms"), national inventory reports (NIRs), biennial update reports (BURs) and biennial transparency reports (BTRs) are all components of the MRV system established for countries under UNFCCC, the Kyoto Protocol and the Paris Agreement. All involve, among others, the compilation, reporting and expert review of national GHG inventories (NGHGI) to the UNFCCC.

[31] In the AFOLU Sector, emissions and removals on managed land are taken as a proxy for anthropogenic emissions and removals (Managed Land Proxy), and inter-annual variations in natural background emissions and removals, though these can be significant, are assumed to average out over time (IPCC 2019). Seagrass in coastal waters is an exception that applies an emissions factor. Conversely, the Global Carbon Budget (Friedlingstein et al. 2023) partitions human-induced land use change effects from other types of naturally occurring terrestrial CO_2 removal (see Figure 2-2).

MRV for NGHGI compilation by countries is underpinned by the TACCC principles, that is: transparency, accuracy, completeness, comparability, and consistency (e.g. IPCC 2006; IPCC 2019; see Box 1-1). These methods form the basis of the aforementioned country-level NIRs in BTRs submitted to the UNFCCC for tracking compliance towards the Paris Agreement goals.[32]

The methods and protocols are generally well-established for quantifying GHG emissions from activities undertaken at the installation/facility and/or sectoral level (e.g. energy, industrial processes and product use, waste) and for land-based GHG fluxes from land parcels, regional land use types and/or the area of the national territory under given land use categories (i.e. AFOLU emissions and removals on e.g. forestland, cropland, grassland, wetland etc).

Inclusion of some novel CDR methods is also emerging, such as the chapters on geological CO_2 transport and storage (Volume 2 and Volume 3 of IPCC 2006; which encompasses BECCS and could be readily extended to DACS; see below), and a proposed method for integrating biochar into soil C stock inventories in the AFOLU sector (appendix 4 to Volume 4, Chapter 2, IPCC 2019; see Table 4-6).

Corporate GHG inventories (and sub-national entities)

Inventory approaches and guidance

Corporate disclosures of GHG emissions and removals and those of cities and sub-national governments are typically guided by the suite of standards, guidelines and tools under 'GHG Protocol'. Presently the GHG Protocol covers the following actions and activities:

- GHG Protocol – Corporate Standard
- GHG Protocol for Cities
- Product Standard
- Project Standard
- Mitigation Goal Standard
- Corporate Value Chain (Scope 3) Standard
- Policy and Action Standard

The nature of GHG inventories (GHGIs) for these entities poses different boundary conditions to that of NGHGIs. Corporate organisational control can be transboundary in nature, while the up- and downstream emission resulting from company value chains leads to calls for scope 2 and scope 3 emissions to be included on top of direct, scope 1, emissions (i.e. those emanating directly from a firm's operations).[33] These arrangements create some complexity for GHG accounting, primarily because of the lifecycle nature of value chain accounting.[34] In

[32] The biennial transparency reports (BTRs) are the basis of implementation of the Paris Agreement's enhanced transparency framework.
[33] Scope 1 emissions are direct GHG emissions that occur from sources that are controlled or owned by an organization. Scope 2 emissions are indirect GHG emissions associated with the purchase by an organisation of electricity, steam, heat, or cooling. Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain.
[34] Some have argued that the Scop1/2/3 approach is an artifact of its time (e.g. when the U.S. was pulling out of the Kyoto Protocol) and is no longer fit for today's decision-making purposes (see Gillenwater 2023).

all cases, these organisational GHGIs are, or should in principle at least be, inherently 'nested' inside one or more NGHGI reporting system; despite them being different scopes, the GHG emissions and reported across the GHGIs should use the same activity data and emission factors.

For nature-based CDR, the GHG Protocol now includes *draft* Land Sector and Removals Guidance (GHG Protocol 2022). Specific attention is afforded therein to the alignment of corporate and NGHGIs, with the complex discussion on the linking of these differing systems highlighting the challenges posed for coherent accounting across companies and countries.

Inventories under compliance-based systems

In most ETSs (e.g. in the EU, New Zealand, California) the MRV applied to covered installations/facilities (Scope 1 emissions) is closely or fully aligned to the IPCC methods for NGHGI compilation and reporting implemented by countries. In the EU, this link is mandated under the Governance Regulation,[35] and in New Zealand, NZ ETS data are used to verify Energy and IPPU sector totals reported in the NGHGI (Ministry of Environment [NZ] 2023). Such GHGI 'nesting' ensures consistency between the installation/facility level reported GHG emissions data and the NGHGIs reported to the UNFCCC by the host countries.

In the U.S. and Canada, national facility-level GHGI reporting programmes (e.g. the EPA Greenhouse Gas Reporting Program; GHGRP) also draw closely from IPCC methods so as to directly inform and verify NGHGI estimates.

Land-based MRV systems also seek to ensure effective 'nesting'. For example:

- In New Zealand, the inclusion of forestry (aboveground biomass) in the NZ ETS allows data collected thereunder to also be used for reporting of LULUCF emissions and removals (Ministry of Environment [NZ] 2023).
- In the EU, LULUCF activity data used to compile NGHGIs by EU member states is required to incorporate tracking data from geographical information systems in existing programmes and surveys, such as the LUCAS (Land Use Cover Area frame Survey) and the Copernicus Programme.[35] The EU's proposed CRCF also seeks to align project-based approaches with national level NGHGI data (in e.g. its Article 4.9; see Section 2.3.2).

4.1.2 MRV for project-based approaches

Rather than land parcel or installation/facility level GHGIs, the MRV discourse around CDR has so far almost exclusively focussed on project-based accounting approaches and methodologies. In these respects, a range of VCM methodologies exist or are under development that support the origination of removal credits for various CDR activities at a project level (Table 2-2). The project-based starting point seemingly stems from the voluntary

[35] Regulation 2018/1999 on the Governance of the Energy Union ("the Governance Regulation")

and novel nature of CDR, and the growing demand for discrete ‘neutralisation’ credits by corporate buyers (Section 2.3.1).

Project-based MRV frameworks and concepts originate from the CDM and the VCM. The general underpinnings are therefore established for application in jurisdictions without economy-wide climate PAMs or national or regional incentives for GHG emission reduction or removal. Indeed, project-based crediting is founded on the basis that an emissions reduction or removal activity would not happen absent of the incentive offered by the sale of the credits (i.e. an activity is only *additional* where other policies, measures or other economic factors pose barriers and/or do not require or incentivise it to be implemented).

Such underpinnings mean that project-based methodologies/MRV have traditionally needed to, inter alia:

- Apply a wide-reaching boundary to capture a broad range of positive and negative GHG effects that could result from project implementation (e.g. the counting of indirect emissions associated with bought-in heat and power, since these are not being regulated through other types of climate PAMs). Wide boundaries can ensure that emission reductions or removals are ‘real’ rather than the product of selective accounting.
- Account for GHG leakage effects that may occur in the wider economy beyond the activity boundary (e.g. to check that market impacts and displacement effects do not pose material impacts, such as with crediting biomass use for energy production/BECCS). The risk of leakage is diminished where these activities are subject to effective climate PAMs (e.g. effective LULUCF management policies and high quality MRV).
- Apply ‘additionality’ testing to ensure that projects go beyond standard practice and regulations etc and thereby to establish the most credible counterfactual baseline scenario (e.g. to assess jurisdiction-specific PAMs to demonstrate that the credited project activity was not mandated or incentivised by local policies, laws or customs i.e. ‘regulatory surplus test’), and to confirm that an alternative baseline scenario of higher emissions and/or lower removals would have occurred absent of the credited activity.
- Establish baseline emissions for a counterfactual baseline scenario, using either projection-based (the most likely course of action in the absence of the activity) or standards-based (emissions of a benchmark solution providing the same function or service) approach.

These features make project-based MRV quite distinct to the MRV applied for GHGI compilation. There are, however, important overlaps that should be considered, as discussed below.

4.1.3 The need for accounting

The two MRV approaches described above—namely, MRV for GHGIs and MRV under project-based approaches—should fit seamlessly together in a consistent way for two key reasons relating to the environmental integrity[36] of the policies through which they are promulgated:

- **Connectivity and attribution**. The crediting of individual CDR activities at the project level should produce the same measurable, consistent, outcomes in the NGHGI of the country which hosts it. Without this connection, a CDR project activity will lack any political utility for the country hosting it and may introduce environmental integrity problems for any resulting credits/certificates (Section 4.3).
- **Avoidance of double counting**. Crediting of a CDR activity within a corporate value chain can lead to double counting: once as a mitigation action *inside* a corporate GHGI, and once again through accounting of the credits as offsets *against* a corporate GHGI.[37] Such effects need to be avoided to maintain environmental integrity for corporate claims related to the VCM.

Robust approaches to MRV must therefore take account of these important accounting aspects. Problematically, the starting points and results of applying the two different MRV frameworks can be quite different:

- GHGIs are wholly *attributional* or *allocational* insomuch as they provide a record of real, measured and recorded GHG emissions and removals.
- Project-based approaches are generally more *consequential* and instead look towards causality by calculating a *notional* difference between what actually happened (attributional GHGI) relative to what might have otherwise occurred (counterfactual baseline GHGI).

While the different approaches often require similar data and measurement techniques to compile an attributional GHGI, they are often conflated, and disentangling the outcomes can be challenging (Section 4.3). Some key differences between the two are summarised below (Table 4-1).

4.2 Project based MRV for CDR

4.2.1 Methodological framework

Most observers have so far contended that CDR must be subject to full lifecycle accounting that covers all up- and downstream GHG effects so as to ensure only the 'net' GHG removal effect is MRV'd and certified (e.g. Tanzer and Ramirez 2019). Full lifecycle accounting is vital in establishing an ex ante assessment of the GHG mitigation efficacy of a given CDR method

[36] Environmental integrity in carbon markets and GHG accounting relates to the way in which actions are measured and reported compared to the true emissions outcome in respect of changes in atmospheric GHG stocks. Accounting must ensure that the actions and outcomes are closely matched.
[37] Hence, beyond value chain mitigation remains a key topic in VCM discussions.

or activity. However, transposing full GHG lifecycle thinking to the crediting of CDR activities into effective policy design can pose some challenges for GHG accounting. Herein the approach to MRV for CDR is considered within two basic accounting frames—consequential and attributional—that could be used to measure CDR at a project level.

The choice of accounting frame is relevant when contemplating the various methodological elements covered in Sections 4.2.3 to 4.2.5 below. The choice of approach should, however, ultimately be informed by the overall goal of the assessment, as set out below.

Table 4-1 Differences in MRV under attributional and consequential accounting*

Frame	Recorded measurement	Goal/Purpose	Use
Attributional (or allocational) (GHGIs)	Typically an ex post *record* of emissions and removals. Notably: ▶ GHGIs are a record of *real* and *measurable* GHG emission and removal attributes associated with an entity	Quantify and assign responsibility to a reporting entity (Gillenwater 2023). The reporting entity is defined by its organisational or installation boundary	Seeks to measure progressive performance of the reporting entity over time. Attributional performance is typically measured relative to a historical benchmark such as a base year.
Consequential (Project-based approach)	Typically ex ante and ex post *estimate* of the consequence of an intervention or activity, at least partially informed by GHGI records. Notably: ▶ Emission reductions are not necessarily real attributes, but rather a consequential measure of a notional outcome (i.e. the 'consequence' of an intervention/activity) ▶ Carbon removals can be viewed as real attributes resulting from an intervention/activity.	Establish a causal relationship between a discrete intervention/activity and outcome relative to what would have otherwise occurred. The intervention/activity is defined by the project boundary.	Seeks to measure the performance of an intervention/activity against a counterfactual scenario over time. Consequential performance is typically measured relative to estimated baseline emissions from an alternative intervention or activity performing the same function or delivering the same service (i.e. a counterfactual).

* The characterisation of MRV approaches set out in the Table attempts to highlight how an attributional approach applies to reporting entities rather than to activities, products or systems (i.e. its rather more 'allocational' than strictly attributional). However, attributional GHGIs can and are applied to activities, products and systems under end-to-end, LCA-type, approaches. Project-based accounting is consequential because it involves the comparison of an attributional GHGI for a mitigation activity *relative* to a—typically estimated—GHGI for a counterfactual scenario (i.e. looks to link causal effects). Consequential LCA also seeks to understand causal relationships in actions, as opposed to more static LCA inventory methods associated with attributional LCAs. The terms allocational and consequential therefore rather relate to how the results are used in practice, as opposed to being strict classifications of the MRV and accounting approach (see also Brander, 2022)

Consequential accounting

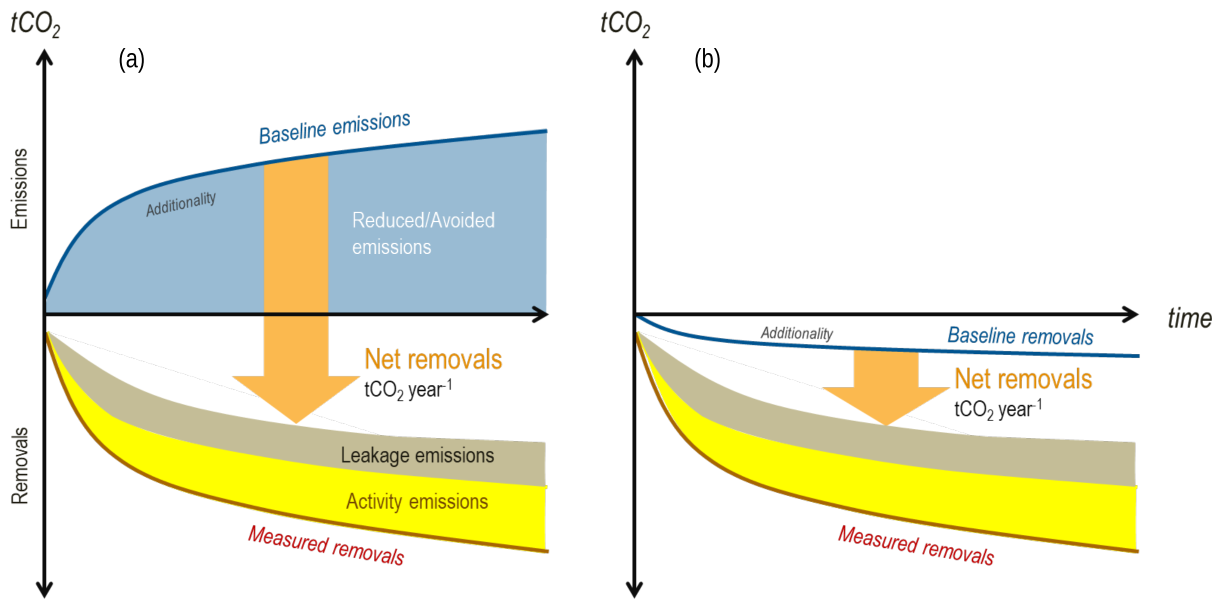
Project-based accounting involves estimating the net GHG effect of implementing a mitigation activity (reduction or removal intervention) relative to how GHG emissions would have occurred in its absence. The approach is consequential insomuch as the goal is to understand and quantify the GHG benefits arising from a specific investment decision. Typically the net GHG effects are assessed according to the change in emissions across the entire value chain of an activity, including potentially wide-reaching consequences (i.e. leakage effects). The actual measured emissions and removals for an activity (i.e. the activity GHGI) is compared to the estimated emissions and removals for a comparable value chain under counterfactual scenario that might have occurred instead of the activity (i.e. a baseline GHGI).

The counterfactual scenario is usually framed in respect of the GHG emissions associated with delivering the same service or outcome as under the project activity but using a different, higher emitting, method. In the case of CDR, however, such framing may not be necessary as, in the case of most novel CDR methods, the absence of any direct intervention would leave a counterfactual scenario involving little or no removals (especially, engineered systems or ocean-based CDR). In other words: there is typically no counterfactual scenario in situations where the only service being delivered is CDR.[38]

Moreover, unlike *notional* calculated emission reductions (Table 4-1), a zero baseline implies CO_2 removals can be viewed as a real attribute that can be measured (with varying levels of confidence) and assigned to an entity performing an activity in a defined location (in most cases). In other words, for emission reductions, the consequence is measured relative to a notional counterfactual (i.e. a baseline scenario), whereas a change in C stock within a defined target reservoir can be measured over time relative to zero and attributed to an activity (i.e. the level of C in the reservoir at the activity start date can be the baseline). The baseline for an emission reduction activity can also be the level of emissions in a base year (e.g. a historical baseline; Figure 4-4; Section 4.2.3).

The typical methodological framework to estimate the credits or certificates to be awarded to CDR activities under a consequential approach is illustrated schematically below (Figure 4-1).

Figure 4-1 Consequential project-based accounting



[38] BECCS can be an interesting exception due to several counterfactuals being possible (e.g. use of alternative fuel sources and no biomass harvesting, or bioenergy use without capture).

Net removals may thus be calculated as:

$$NR_p = BE_p - (MR_p + AE_p + LE_p) \qquad \text{[Equation 1]}$$

Where;

NR = Net removals (tCO_2 or tC)
BE = Baseline emissions/flux (tCO_2 or tC)
MR = Measured removal/C stock change (tCO_2 or tC)
AE = Activity emissions/flux (tCO_2 or tC)
LE = Leakage emissions (tCO_2 or tC)
p = relevant measurement period (e.g. 1 year)

Notably, a consequential methodological approach can result in calculated net removals including a quotient of emission reductions/avoidance (i.e. where emissive activities are included in the baseline but not in the project; the blue wedge in Figure 4-1(a)). An example would be reduced fossil fuel use by tractors in a no-till agriculture SOC enhancement project activity. Alternatively, in some situations a baseline may not contain any emissions and rather assume a level of ongoing removal which are enhanced by the activity (Figure 4-1(b)). An example could be an assumed level of natural, ongoing, removal by the target sink absent of any human perturbation. Both may also be possible at the same time (i.e. a removals baseline below zero and emissions baseline above zero).

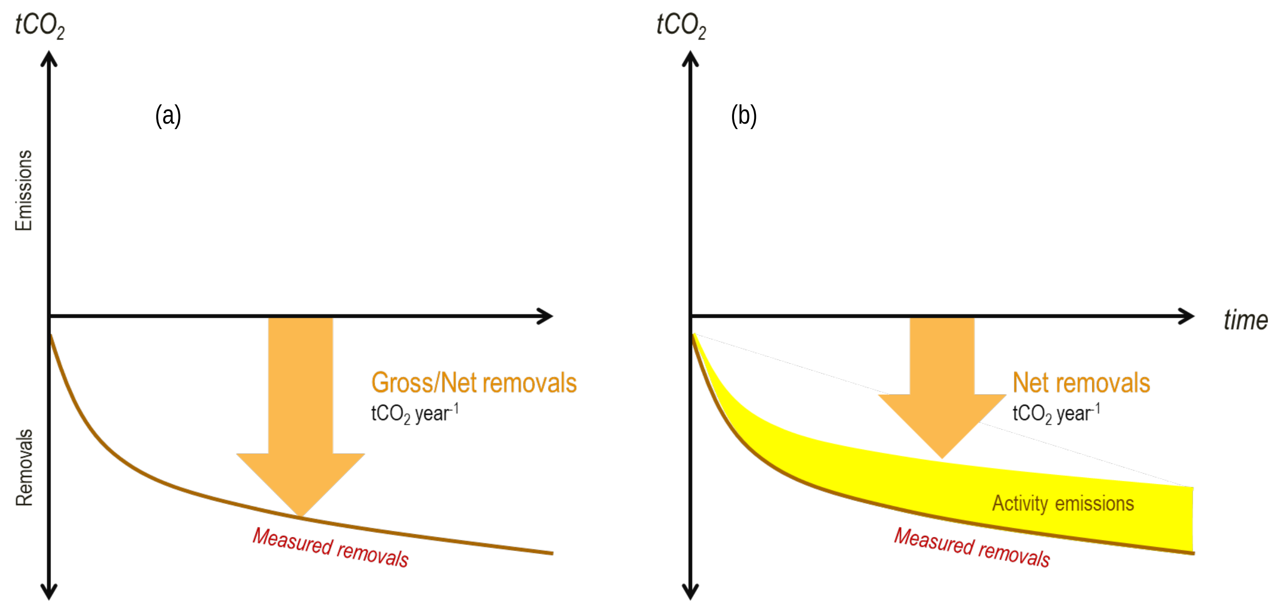
Attributional/Allocational accounting

An attributional or allocational accounting approach involves calculating net removals without a counterfactual or baseline scenario. Instead, the approach measures the relative change in removal over time that is directly attributable to a specifically defined activity site (i.e. the amount of CO_2 drawdown over a year based on an annual GHGI for a farm, a field, a parcel of land, a DAC facility or a biomass-fired power plant equipped with CO_2 capture). Either gross or net could be measured (respectively, Figure 4-2 (a) and (b) below).

Such an attributional or allocational methodological approach can be applicable where the removal baseline is zero under either a temporal/historical (i.e. the level of removals at activity start date) or an economic approach (i.e. level of removals under a counterfactual scenario absent of the activity).

The choice of gross or net is discussed further below (Box 4-1).

Figure 4-2 Attributional/allocation project-based accounting



4.2.2 Boundaries and leakage

For project-based approaches, the formula in Equation 1 above must be informed by data gathered from different components across the value chain of an activity. A project boundary determines which components within a system should be MRV'd, thus providing the basis for certifying and crediting a given management intervention or activity. The project boundary is primarily considered in a spatial context, which may be defined as:[39]

> The emissions by sources and removals by sinks and reservoirs that are under the control of the activity developer and that are reasonably attributable to the project activity. The associated sinks and reservoirs may be geographically delineated.

In some cases, a temporal boundary may also be addressed, for example, in relation to length of crediting and monitoring periods, and any post-crediting monitoring requirements.

Project leakage should also be measured, which can be defined as:

> The emissions by sources and removals by sinks and reservoirs that are not under the control of the activity developer but are reasonably attributable to the project activity and can be measured.

A first choice for project-based methodological design is therefore which sources and sinks to include and exclude within the monitoring plan, and what sources of leakage may need to be taken into account.

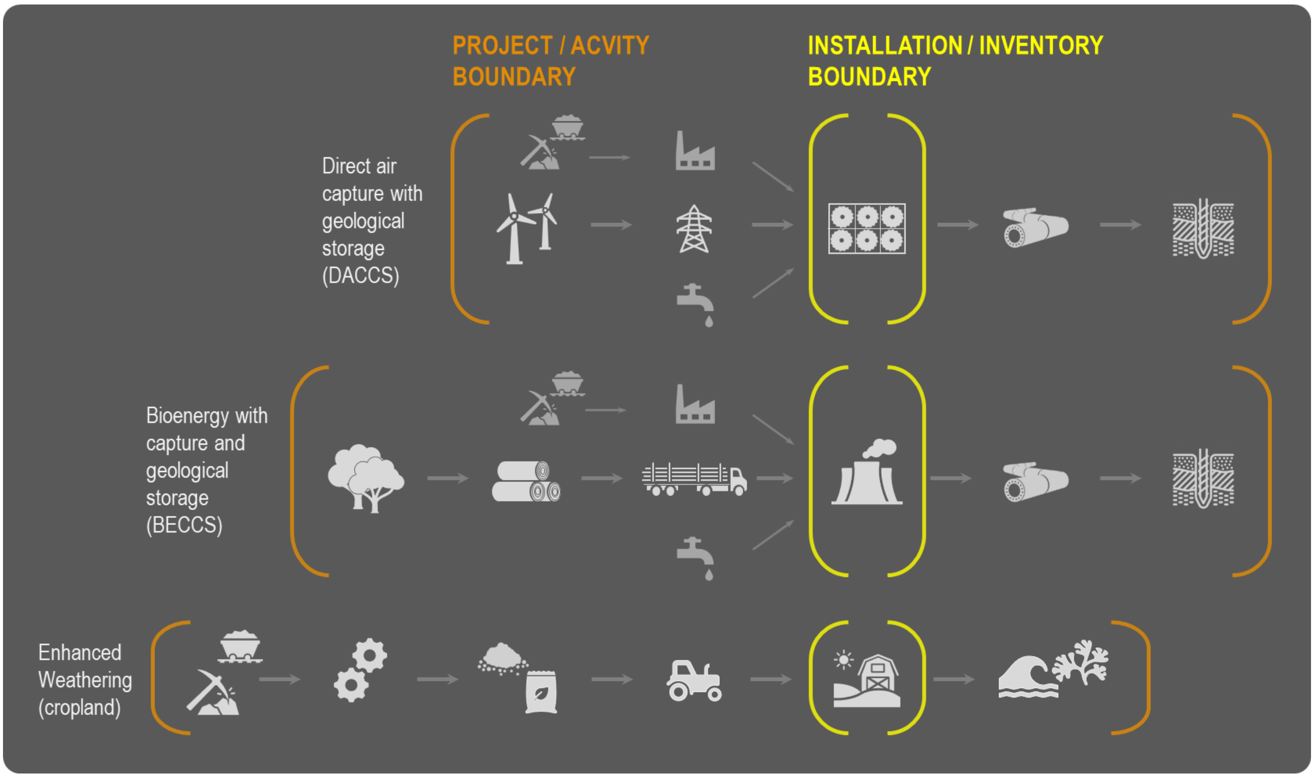
In an attributional approach, the project boundary may be defined as:

[39] Drawing from various sources, including the clean development mechanism.

Emissions by sources and enhanced removals by sinks and reservoirs within a geographically delineated area under the control of the operating entity and that are reasonably attributable to the activity including through a technical connection.

Drawing from the definitions outlined, the figure below illustrates how the different boundary conditions for CDR methods can be applied under different accounting approaches (Figure 4-3).

Figure 4-3 Boundary conditions for CDR under different accounting approaches



In all three CDR methods shown above (Figure 4-3), the boundary in an attributional, or rather, an allocational, accounting approach is limited to the site where the removal takes place, be it the CO_2 capture installation or the field or farm subject to EW material deposition (shown in yellow). Any emissions associated with the activity but occurring up- or downstream of the CO_2 removal point fall outside of the allocational CDR MRV boundary. Although these sources are linked to the activity, they can be excluded from the calculation of measured removals or activity emissions. Such an approach can be relevant where these value chain emissions are effectively regulated by other climate PAMs (e.g. an ETS or carbon tax). This is a particularly critical assumption if the resultant CDR credits can be used for compliance by emitters within the CDR value chain (see Box 4-1).

The range of implications for the clusters of CDR methods are summarised below (Table 4-2).

Table 4-2 Activity boundary and leakage considerations for CDR clusters

Consequential	Attributional/Allocational
Biological capture and storage — Capture and storage takes place in the same delineable geographical location	
Boundary: capture and storage system can be bounded and delineated based on the individual land parcels subject to the CDR intervention (afforestation, SOC enhancement; IFM). Partially closed storage system. Fate and behaviour of C in target sink/reservoir can be predicted providing basis for delineating activity boundary (e.g. above ground biomass). SOC can present challenges. Leakage: conversion of a land parcel (field of farm) to a CDR site may increase pressure on surrounding fields/farms (e.g. due to changes in productivity). May call for jurisdictional approach to implementation to potentially capture such effects. More broadly, systemic conversion of agricultural land to forests may displace agriculture to other areas, increasing pressure on farmland or destruction of forests and conversion to agricultural land (i.e. deforestation, so-called indirect land use change; iLUC). Challenging to identify and quantify.	Boundary: as for consequential. Leakage: iLUC risk diminished or controlled where activities are constrained to geographical regions with effective land sector climate PAMs. In such situations, iLUC effects should also be recorded in the relevant jurisdictions' NGHGI and accounted for against relevant GHG goals (e.g. in the NDC).
Engineered geological storage — Capture and storage may or may not take place in the same delineable geographical location	
Boundary: entire system of CO_2 capture (DAC, BEC), CO_2 transport, and CO_2 storage included in activity boundary. All system components (installations/ facilities) can be identified. Closed storage system. Fate and behaviour of the CO_2 in target sink/reservoir can be predicted providing basis for delineating activity boundary as a single system/entity. Lifecycle upstream (emissions from imported heat, energy and materials for CO_2 capture) and downstream (emissions associated with CO_2 transport and storage) can be identified and included in activity boundary. Leakage: iLUC effects may arise where e.g. agricultural land is given over to dedicated bioenergy production for BECCS.	Boundary: only CO_2 capture (DAC, BEC) installation included in the boundary. Lifecycle emissions (up- and downstream) subject to other, separate, climate PAMs to control emissions (e.g. an ETS). Leakage: iLUC risk can be diminished or controlled as described above.
Engineered biological storage — Capture and storage takes place in different, part delineable/part unbounded, geographical location(s)	
Boundary: entire system of material acquisition (biomass, minerals), processing (e.g. pyrolysis; grinding), transport and deposition on land can be identified and included in activity boundary. Most system components (installations/facilities) in the system can be defined, providing basis for crediting as a single system. Lifecycle emissions included in boundary. Open storage system. Makes boundary difficult to delineate. Fate and behaviour of C stored in materials (biochar, carbonates, bicarbonates) in the target sink/reservoir(s) cannot be accurately predicted and bounded. Leakage: diversion of biomass into biochar may drive some leakage effects. Positive impacts may arise from reduced soil conditioner inputs. Re-oxidation of stored C outside of activity boundary (downstream) can be considered as leakage risk.	Boundary: only the biochar production installation (pyrolysis) or the field where minerals spread (EW). Lifecycle emissions (up- and downstream) may be excluded where they are subject to other climate PAMs to control emissions (i.e. emissions from fossil fuel use; agricultural policy related to agriculture/cropland GHG emission controls). Leakage: risks diminished or controlled through existing climate PAMs.
Ocean-based CDR — Capture and storage primarily takes place in the same, but largely unbounded, geographical location	
Boundary: entire system of material acquisition (minerals), processing (e.g. grinding; sea water extraction and pumping; algae management), transport and deposition into the ocean to be included in activity boundary. Emissions associated with system inputs included (lifecycle). Emissions from EC mCDR may occur on land at existing GHG emitting installation (e.g. electricity generating installation/facility). Open storage system makes activity boundary difficult to delineate. Fate and behaviour of C in materials (e.g. carbonates, bicarbonates, biomass) in the storage medium cannot be accurately predicted and bounded. Leakage: unclear.	Boundary: only gross removal by the mCDR technique. Lifecycle upstream (emissions from imported heat, energy and materials) and downstream (emissions from transport; storage) subject to other climate PAMs to control emissions (e.g. an ETS). Any onsite (activity) emissions to be included (e.g. ship emissions).

Under project-based accounting, the converse applies. Here, wide boundaries are adopted covering the entire value chain, and any up- and downstream emissions are netted off against the amount of measured CO_2 removal at the main installation site. If resulting credits can be used by emitters in the value chain, double counting will occur (Box 4-1).

For biological capture and storage activities, the boundary in both approaches would be limited to the field or farm.

While there is a general inclination to consider only project-based approaches towards CDR, there are critical boundary effects that need to be assessed to ensure policy coherence and consistency and transparency in GHG accounting. Such considerations need to take clear account of differences in regional settings and circumstances in terms of economy-wide climate PAMs (see Box 4-1). As such, there can be reasons to consider attributional approaches to CDR at an installation level, as reviewed further below.

4.2.3 Baselines and additionality

An integral component of robust CDR MRV is considered to be the requirement for certifiable and creditable removals to be *additional.* Additionality is a concept to link causality insomuch as it seeks to assess whether and to what extent a mitigation intervention/activity (e.g. CO_2 removal) goes beyond levels that could be expected without the given policy/programme. Additionality demonstration is therefore a procedure that seeks to describe how the reductions or removals attributable to a certifiable/creditable activity are not the same as—or in other words, are *additional to*—the level of emissions or removals that would have occurred in a counterfactual baseline scenario (i.e. absent of the availability of crediting/certification).

Additionality can be further divided along lines of, inter alia:

- **Environmental additionality**. Where any emissions or removals exceeding a pre-agreed crediting baseline, such as a standardised benchmark for emissions or removals for a given activity type, are considered additional; or
- **Project additionality**. Which may take account of a standardised benchmark but also other factors that may influence management interventions, including regulatory surplus and the economics associated with the investment with and without the incentive offered by credit generation.

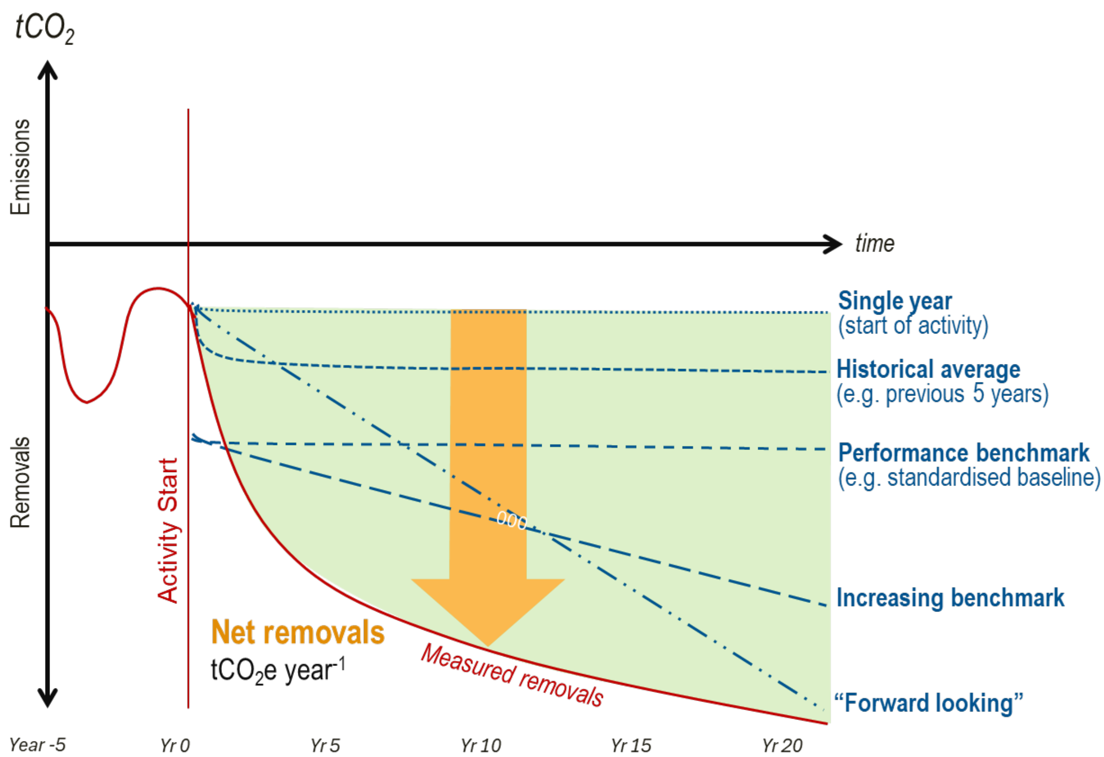
To implement the concept of additionality in practice, a baseline scenario is needed that describes how emissions/removals would develop absent of the implemented credited activity. The baseline scenario provides the basis for developing a crediting baseline that acts as a reference level against which the GHG reductions/removals effectiveness of an activity can be judged, measured and quantified (Figure 4-1).

In the case of nature-based biological capture and storage systems, and to an extent, EW and mCDR, environmental additionality and crediting baselines may also encompass technical aspects relating to how much of any measured CO_2 removal monitored during activity implementation is actually attributable to the intervention (i.e. human perturbation) rather than naturally occurring, ongoing, CO_2 drawdown by the C sink in question.

A crediting baseline is therefore drawn as a reference level against which to calibrate observed and measured CO_2 removal relative to both (i) a counterfactual activity baseline scenario and in some cases (ii) naturally occurring uptake of CO_2 by plants and other environmental processes (e.g. weathering). A third baseline component to consider is political. Crediting baselines may also be adapted by, for example, seeking to downwardly adjust the level over time to account for future increases in climate ambition by countries where the activity is hosted.

A range of possible crediting baseline approaches are illustrated below (Figure 4-4).

Figure 4-4 Illustrative examples of CDR crediting baseline types



The illustrative baseline examples shown above incorporate the following:

- **Projection-based approaches**. Methods that project forward the future baseline emissions and removals for a counterfactual scenario for the given activity, drawing from data such as:
  - *Historical removals*. The level of removals achieved prior to the implementation of the activity (multi- or single-year time series)
  - *'Forward looking'*. Approaches that take account of future policy goals and drivers to adjust the baseline towards progressive climate action. In these respects, approaches such as 'baseline contraction factors' (BCF) are mentioned in climate

policy discourse but have not yet been fully defined (UNFCCC 2023). Noting the connection to future increases in ambition, some observers have suggested the use of an 'ambtion coefficinet' through which to establish BCFs (Michaelowa et al. 2022).

- **Standards-based approaches**. Methods that estimate the emissions and removals for a counterfactual scenario using a standard rate for the given activity, for example:
  - *Performance benchmarks*. Fixed or dynamic emission, removal or flux rate that determines the crediting baseline for a given level of activity (e.g. best-in-class or "top-runner" methods such as top 20th percentile; standardised baselines). Performance benchmarks can also be modified over time in a forward-looking way (e.g. assumed to have increasing removals over time, thus reducing the future volume of credits).

Box 4-1 Integrating CDR into ETSs – a case for attributional accounting

The underlying reasoning for applying consequential accounting in existing reduction and removal crediting programmes were outlined above (Section 4.1.2). In jurisdictions with economy-wide GHG controls and far-reaching climate PAMs the same reasoning may not apply (e.g. carbon pricing, such as a cap-and-trade ETS, applied to all sectors). Rather a different set of MRV and methodological considerations are posed, focussed on attributional approaches that can account for possible interactions with existing economy-wide regulation and related cross-sectoral effects. The following issues are relevant in these respects:

- Boundary and leakage. Up- and downstream emissions associated with a CDR activity may not need to be accounted for because they are already regulated and/or priced under existing climate PAMs (e.g. emissions associated with imported heat and power used in CDR processes may already be regulated under an ETS). Such parallel PAMs should already serve to restrict lifecycle GHG impacts. In some cases, the C reservoirs where storage takes place may also already be covered by climate PAMs (e.g. geological CO_2 storage sites included as qualifying installations within the EU ETS).
- Baseline and additionality. If current far-reaching climate PAMs do not incentivise a CDR activity, then an activity can be considered de facto 'additional'. If new policies are created to incentivise CDR, the policy can be considered to close any 'additionality gap' at the policy rather than programme or project level. On this basis, case-by-case activity level additionality testing could be disregarded.
- Avoidance of double counting. If the credits are used as compliance instruments within existing climate PAMs, double counting can occur. For example, if a fossil fuel power plant provides at least some of the heat and power to a DACS plant, the power plant's emissions may not need to be deducted from CDR credits issued to the DACS plant. If the power plant operator subsequently seeks to acquire the resulting CDR credits for the purposes of offsetting/compliance against those very same emissions, then double counting will occur.

In the circumstances described, a case can be made to apply attributional accounting approaches counting either the gross removals (which would apply if the onsite emissions are already covered by existing climate PAMs; Figure 4-2(a)), or the net removals after taking account of onsite emissions (Figure 4-2(b); where the onsite emissions are excluded from existing climate PAMs). However, in situations where CDR credits are valued higher than emission reductions, systemic challenges and/or perverse outcomes can arise (see Section 4.3.2).

Problematically, all methods for baseline determination and additionality testing face challenges due to the inherent difficulties in determining counterfactual, or "what if", type scenarios. Experiences with crediting programmes over the past 20 years or so suggest that information asymmetry can impair consistent assessment of additionality across a wide variety of circumstances and settings. Uniform project-by-project additionality assessment is thus hard to achieve leading to unevenness in project registration. Such problems can be addressed by using standards-based approaches that employ a consistent baseline for all of the same types of activity (i.e. a standardised baseline) and/or including for given activity types in a specific area (i.e. a jurisdictional baseline). However, the risk of adverse selection can arise where activities and environmental conditions are heterogenous (Box 4-2).

Box 4-2 Standardised baselines and adverse selection

Jurisdictional baselines involve the use of a standardised benchmark factor or emission/removal factor for a given land type or CDR method within a given geographical area (e.g. an approved CO_2 flux for a type of land parcel in a given area, region or country). Such jurisdictional approaches can avoid challenges for project-by-project baseline and additionality determination.

However, adverse selection or selection bias can also arise, especially in situations where there is heterogeneity and information asymmetry between project operators and CDR certification operators. Where the certification mechanism is optional and C stocks are heterogenous (e.g. forests; soil organic carbon), selectivity in registering activities can lead to circumstances where, by virtue of site-specific circumstances (e.g. biophysical characteristics or the current state of dynamic equilibrium, such as age class and structure of a forest), only those activities that offer the greatest potential for C stock accumulation relative to other parcels of land across a jurisdiction are registered. This may not result in an increase in net removals within a jurisdiction, but rather produce CDR credits for activities on land parcels that lie above the selected jurisdictional baseline (i.e. they may not be additional). Non-additional certification poses risks to environmental integrity.

Crediting baselines and additionality determination relying on standardised benchmarks therefore pose challenges for optional schemes in heterogeneous situations. Activity-level dynamic baseline approaches involving control plots to set a crediting baseline can be an alternative approach.

Furthermore, most of the current knowhow for baseline setting in project-based methodology design draws from emission reduction activities, and experiences with developing removals-specific crediting baselines are extremely limited (Michaelowa et al. 2021). Notably, while baselines are essential to calculating *notional* emission reductions, removals—like emissions—can be viewed as *real attributes* that can be measured without necessarily referring to a counterfactual scenario (Table 4-1).

Challenges for baseline-setting are further exacerbated by the lack of experience in establishing project-based methodologies in jurisdictions with economy-wide climate PAMs (e.g. in the EU). In such circumstances, a wide range of other climate PAMs as well as complex energy and land PAMs will influence technology choices and investment decisions, further hampering baseline scenario determination and additionality testing. In the EU, previous considerations of so-called 'domestic offsetting projects' under the EU ETS faltered over concerns about the lack of additionality relative to the already wide-ranging climate PAMs in place (e.g. see IEAGHG 2014 for a discussion of EU 'DOPs' and 'COPs').

Applying forward looking baselines such as a BCF will intentionally erode the level of certificates or credits awarded to a CDR activity over time. Yet this can undermine the investment case and impact upon additionality (e.g. financial additionality tests). Equally, fixed crediting periods may also be counterproductive (Box 4-4). Deterring and curtailing the continuous ongoing operation of a CDR activity will significantly impair investment decision-making and ongoing operation. Forward looking baselines therefore require some care when considering CDR activities.

Baselines and additionality are closely related meaning that their determination and demonstration can often be combined into a single assessment: an activity may be considered *environmentally* additional if it outperforms a predetermined standardised baseline; or, an appropriate baseline may be determined through project additionality assessment that considers *regulatory surplus*, *common practice* and *financial* additionality of multiple baseline scenarios. The key to additionality testing is to show that the project activity is not the same as the baseline activity—if this is the case, the project is business-as-usual and therefore not additional.

These two bases for baseline and additionality determination are considered further below.

Standardised baselines (solution- or jurisdiction-level) and additionality

A crediting baseline can be established separate from additionality considerations (Michaelowa et al. 2021), for example, in circumstances where existing targets are in place (e.g. policy goals imply a pre-determined performance benchmark for a given activity or set of solutions; Figure 4-4).

For biological capture and storage, an example is the development of a forest reference level (FRL) or use of base periods, such as those established under the EU's LULUCF Regulation (e.g. for cropland and grassland). In such situations, a fixed performance-based crediting baseline may be determined ex ante for all solutions included with the scope of a CDR certification programme (i.e. establishing baselines at the CDR method-level rather than the discrete activity-level).

Standardised or jurisdictional baselines infer additionality at the policy or programme level: any activity that leads to measured removals in excess of the performance-based crediting baseline can be considered additional, and vice versa. Adverse selection remains a problem, however (see Box 4-2).

For engineered CDR methods, given the cost of implementation and the lack of a business case other than climate change mitigation, a standardised baseline of zero removals and full additionality may be relevant in many circumstances. All such CDR methods are nascent, will be a first-of-a-kind in many locations, and will not be deployed absent of a mandate or incentive such as crediting/certification.

Project-specific baseline and additionality testing

Activity-specific baseline determination and additionality demonstration involves applying procedures that take account of the individual circumstances of each activity that seeks registration for certification/crediting. Such an approach is essential if consequential approaches are considered necessary and standardised baselines are deemed to be unsuitable or pose excessive risks to environmental integrity through adverse selection.

Under this approach, case-by-case assessment and approval for each proposed candidate certifiable activity is necessary. However, activity-specific assessment introduces other types of problems, including:

- Significant administrative burden for system governance, and
- Challenges for harmonisation, taking into account the different economic and environmental circumstances across regions and countries.

Drawing on the discussions above, a provisional logical framework for assessing CDR additionality is set out below (Figure 4-5). The log-frame therein shows three different pathways through which to assess additionality and highlights the intimate connection between baselines and additionality. Notably, while baseline and additionality are viewed as essential features of CDR MRV under consequential approaches, more straightforward attributional approaches could simplify such matters, especially in jurisdictions with far-reaching climate PAMs.

In these respects, in an EU context, Runge-Metzger and Wehrheim (2019) note that:

> "What matters are the changes in removals and emissions compared to a particular reference year. In order to identify these additional changes, the inclusion of LULUCF into national commitments are calculated against well-defined benchmarks or reference years and these are developed in the accounting rules." (Runge-Metzger and Wehrheim 2019, p. 168)

Their view is seemingly that, at least at the national level, a CDR baseline is best informed by a reference year or standardised benchmark rather than activity specific baselines.

Furthermore, the accounting basis outlined by Runge-Metzger and Wehrheim (2019) will result in countries applying attributional approaches to LULUCF accounting in NGHGIs and will—through the Managed Land Proxy[31]—rightly or wrongly allow them to account and make claims for any naturally-occurring ongoing CO_2 removal on managed land (irrespective if it can be attributed to a specific intervention).

Furthermore, to achieve coherence between NGHGIs and activity level crediting, more straightforward attributional approaches to CDR crediting may be relevant, especially when framed in the context of net zero accounting (see Section 4.3.1).

Baseline and additionality considerations for different CDR clusters are reviewed below (Table 4-3).

Table 4-3 Baseline and additionality considerations for CDR clusters

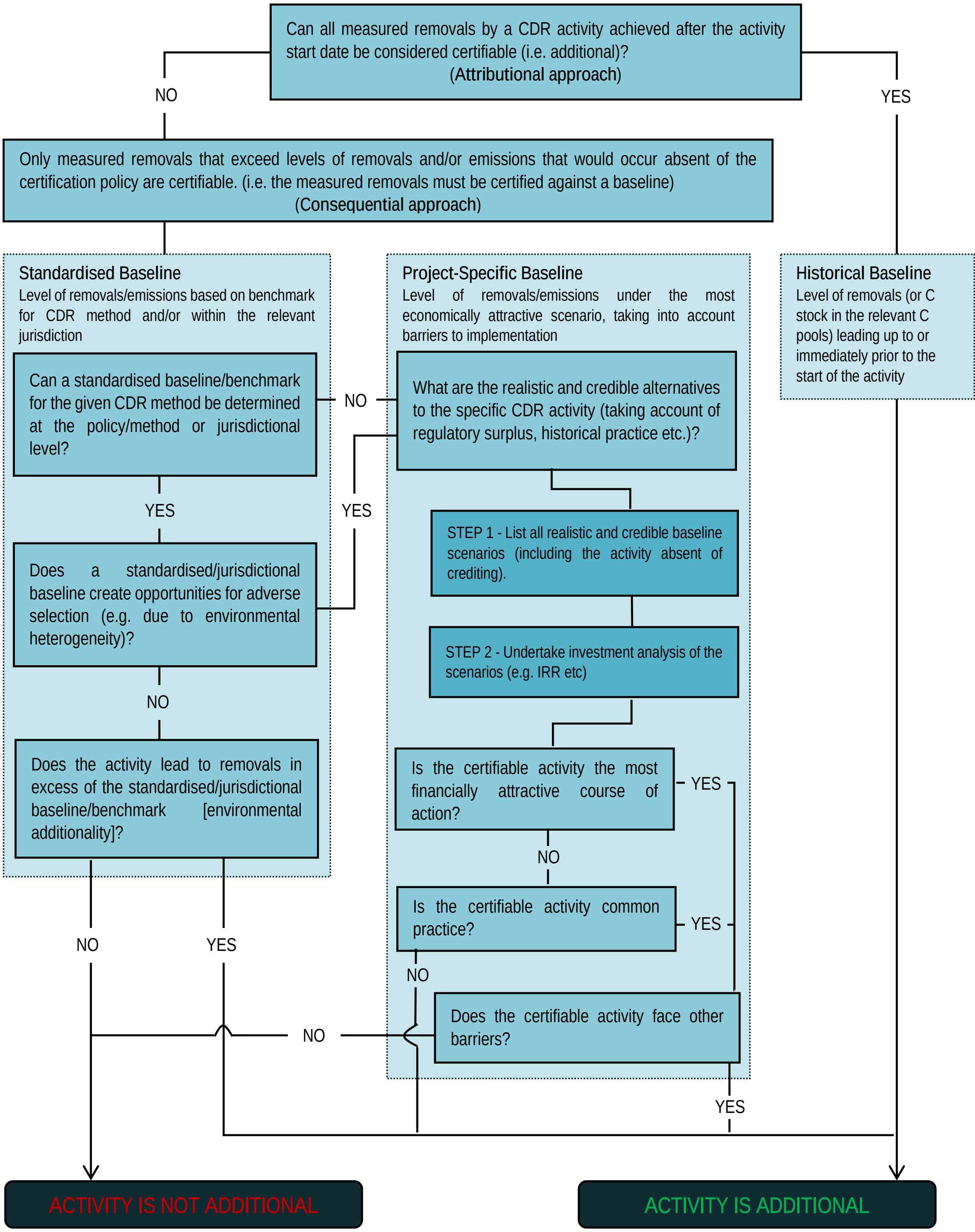
	Consequential	Attributional/Allocational
Biological capture and storage	Baseline: standardised (jurisdictional) or project-specific Additionality: environmental additionality or project-specific.	Baseline: Historical (level of removals leading up to or immediately prior to the start of the activity). Additionality: not applicable (all additional)
Engineered geological storage	Baseline: standardised (benchmark) of zero removals Additionality: all additional	As for consequential
Engineered biological storage	Baseline: standardised (benchmark) of zero removals may be relevant. BC: may call for a counterfactual of the additional of organic carbon to soil (e.g. biosolids that would otherwise spread on land are instead used as biochar feedstock and then spread on land). EW: some incidental fertilization may occur, reducing the need for fertiliser addition. Additionality: project-specific additionality testing may be required in cases where co-benefits offer significant economic incentives (e.g. soil conditioning through liming with residual EW; organic waste stabilisation such as biosolids for biochar production—disposal to land may be otherwise prohibited)	As for consequential
Ocean-based CDR	Baseline: standardised (benchmark) of zero removals Additionality: all additional	As for consequential

4.2.4 Monitoring and measurement

Monitoring the level of measured removals achieved by a defined CDR activity is perhaps the most challenging aspect of CDR MRV. Difficulties arise because of fundamental differences in the way in which the process and rate of CO_2 drawdown can be observed and measured:

- In some CDR methods, the CO_2 flow/flux into sinks and reservoirs can be directly monitored and measured (e.g. metered volume of supercritical CO_2 injected into a well bore or the mass of C in biochar applied to soil).
- In others, CO_2 drawdown can only be inferred by measuring incremental net C stock changes in various terrestrial C pools over time (e.g. above ground biomass in forests or soil carbon as SOC or SIC). In many cases, errors arising from subtracting two large and uncertain C stock estimates may exceed anticipated levels of C stock enhancement (i.e. no discernible C stock change can be confidently observed).
- For some methods it is virtually impossible to measure and detect small C stock changes in a large C pool (e.g. changes in ocean carbonate attributable to OAE) or to discern the amounts of C added to a reservoir relative to pre-existing C levels in that reservoir (e.g. especially for open systems, such as biochar additions to the soil C pool or EW products). Conversely, in some cases, the physical boundaries of the C store can be observed and delineated (i.e. in closed systems such as geological CO_2 storage sites or biomass burial chambers; through geological survey techniques).

Figure 4-5 A logical framework for considering CDR activity additionality



The dynamic state of biological and oceanic C stocks also means that inter-annual variations in emissions and removals will occur over time due to both natural variance (e.g. climate and weather) and human interventions and perturbations (e.g. forest management, harvesting, climate change). Open questions have been posed over the validity of accounting for the former by countries (i.e. under the Managed Land Proxy) but discerning natural variance from human intervention can also be problematic. In the case of biological capture and storage methods, removals and emissions will also occur simultaneously from the same parcel of land, but C stock change methods provide only an indication of net CO_2 flux.

For the reasons outlined above, almost all CDR monitoring relies on some modelling to predict the possible C stock changes and/or CO_2 flux rate under a known set of environmental conditions. Model estimates can, in many cases, be calibrated by observations (i.e. monitoring). The size of the C stock in many systems, and the destructive nature of analytical methods (e.g. SOC measurement through loss on ignition tests) means, however, that only statistically significant observations/sampling can be carried out (rather than the entire C reservoir being measured). The use of tracers (e.g. radionuclides) offers a proxy means to track C movements in open system sinks and reservoirs.

In the case of consequential approaches, additional monitoring challenges arise in respect of data collection for up- and downstream components. Often, estimated emissions for material and energy inputs draw from published, standardised, emission factors for different system inputs, rather than direct measurement and monitoring.[40] Emissions factors can be subject to wide variations, especially for materials inputs.

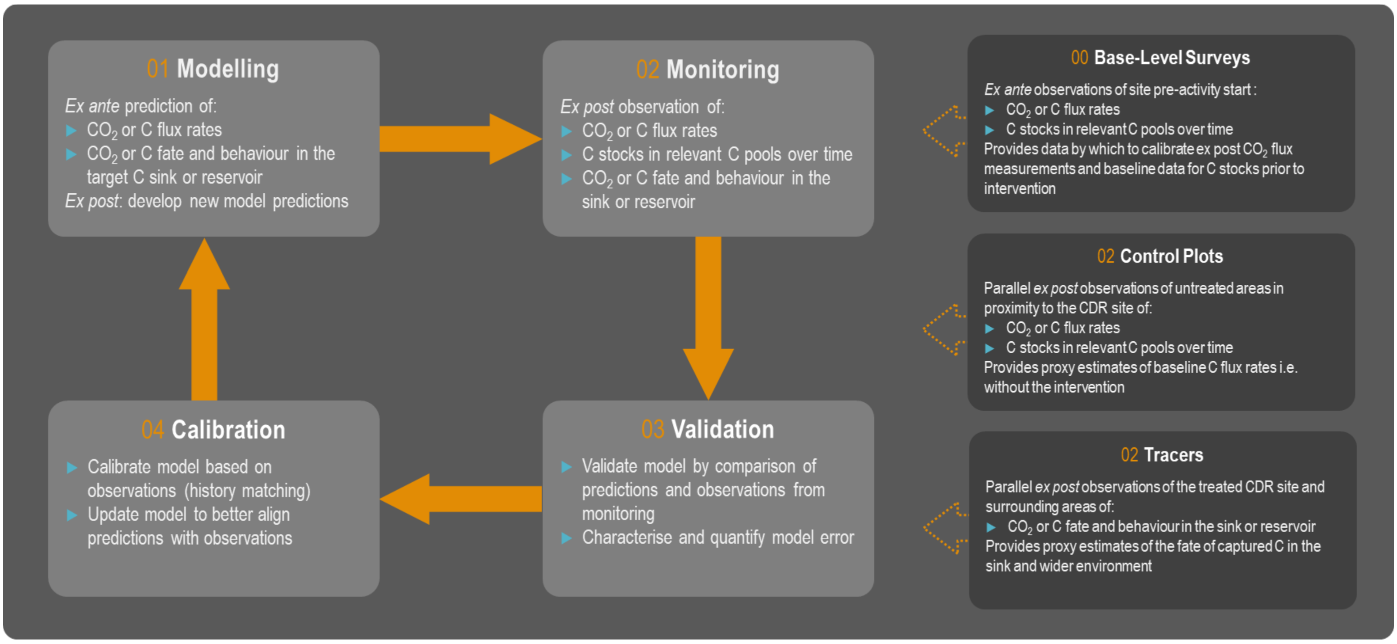
In principle, an idealised protocol for CDR monitoring would cover the following process flow:

- Prior to activity start:
  - ↳ Model the expected fluxes, fate and behaviour of CO_2 and C in the CDR system
  - ↳ Measure background CO_2 fluxes to provide future calibrations ('base-level' survey)
- During activity implementation:
  - ↳ Monitor and measure the system post activity start;
  - ↳ Compare the observations to the ex ante modelled predictions (and base-level surveys and control plot data where relevant); and,
  - ↳ Update the model based on observed behaviour and develop new model predictions (calibration, sometimes called 'history matching').

The cycle would be repeated through relevant monitoring periods to enhance system understanding and build confidence in its efficacy. Many CDR methods may also require monitoring and measurement data from control plots and tracers (Figure 4-6).

[40] Emissions factors offer an estimate of the emissions rate for a unit of input material. System inputs (activity data) are monitoring and measured, but the emissions are only estimated by multiplying the activity data by the emission factor.

Figure 4-6 Idealised CDR monitoring and measurement process flow



Note: the term 'base-level survey' rather than baseline is used to avoid confusion with crediting 'baselines'. Source: authors own interpretation

The idealized workflow notwithstanding, many CDR methods face significant challenges to accurately monitor and measure C fluxes and stocks, posing questions over the acceptability of different models, methods and data sources. In these respects, Runge-Metzger and Werheim (2019) suggest the following for conventional CDR in EU climate policy:

> "As there are still many uncertain elements about the fluxes of CO_2 the land use sector generates, much attention has been paid to how to better monitor and account for these emissions. One can expect that new technologies such as Earth monitoring and space observation will become a useful support to the statistical efforts that have so far been undertaken." (Runge-Metzger and Wehrheim 2019, p. 177) [and that] "Better modelling integrating agriculture, forestry and land use should progress considerably in the coming years…This will likely lead to the further evolution of LULUCF reporting and accounting in the coming decade, which will gradually allow for its complete integration into EU climate policy." (Runge-Metzger and Wehrheim 2019, p. 178)

In considering MRV uncertainty for novel CDR, Mercer and Burke (2023) noted the following in respect of enhanced weathering:

> "Policymakers … could ask: How is it practicable to monitor silicate rock dust spread on agricultural land? Is it cost-effective and scientifically sound to sample CO_2 drawdown at years 1, 5, 10 and 20 before determining the stability of the GGR, or can a light-touch monitoring regime that utilises modelling of ERW characteristics (particle size, silicate content, soil pH, climate, etc.) and past experience provide GGR assurance? What are the trade-offs of a light-touch approach, beyond cost, in terms of sink stability against one where continuous monitoring is prescribed?" (Mercer and Burke 2023, p. 36)

Thus, presently there are gaps between the hypothesized idealised monitoring workflow in Figure 4-6 and what is scientifically and economically feasible today.

Policymakers grappling with these questions have tended to fall on the side of a precautionary approach, wishing for robust MRV to be implemented before offering clear incentives for any such climate mitigation solutions. For instance, political acceptance of geological CO_2 storage as a climate mitigation strategy took many years and needed to be underpinned by robust regulatory standards for, inter alia, site selection, development, operation, monitoring and closure, and include defined responsibilities for stewardship of the C store and allocation of liability for any carbon reversal (see below).

The extent to which other types of CDR methods could shortcut these requirements remain subject to significant debate. Today, CDR methods such as OAE cannot draw upon effective observations and measurement of CO_2 fluxes or detect small C stock changes in a spatially delineated ocean area, meaning that any certification or crediting would entirely rely on modelled CDR estimates. Accepting this limitation for one suite of CDR methods may have repercussion for existing standards that require other CDR methods to apply rigorous and costly monitoring to gain certification.

Indications are that, at least in early-stage deployment, a high bar is likely to be set until maturity and confidence in the methods grow. At future points, relaxation of monitoring standards could be envisaged where confidence in models grows and observation becomes cheaper. As Runge-Metzger and Werheim (2019) note, much hope is being pinned to enhancements in Earth observation systems and so-called "digital MRV" systems. For example, the preamble to the EU's proposed CRCF[20] suggests that:

> "In the context of carbon farming, the use of available digital technologies, including electronic databases and geographic information systems, remote sensing, artificial intelligence and machine learning, and of electronic maps should be promoted to decrease the costs of establishing baselines and of monitoring carbon removal activities" (para 7)

Ho et al. (2023) on the other hand note that, at least for OAE:

> "It is unlikely that technological innovation will dramatically reduce this computational cost [for running ocean biogeochemical models] in the next 5–10 years" (p. 8)

A summary assessment of the monitoring aspects is set out below (Table 4-4).

Table 4-4 Monitoring and measurement considerations for CDR clusters

Modelling	Observation (monitoring)
Biological capture and storage Above ground biomass (AB): growth rate of different tree sp. under varying environmental conditions is well understood and can be modelled. Other C pools, including soil: default factors for C stock changes exist in IPCC Guidelines. Widely applied for LULUCF sector NGHGI compilation. Many assume 'no change' (tier 1) as default unless a land use change is recorded. Soil models: well established and form a core part of existing methodological approaches to SOC projects in the VCM (e.g. VCS VM0042). IPCC 2019 introduced new soil C model provisions.	AGB: Allometric models well established. Can measure standing C stock (based on tree size surveys), which may be supplemented by remote sensing data on tree cover and density. Other C pools. Some techniques such as LiDAR being developed for below ground biomass. Soil C: field measurement highly variable, even within a field. Sampling regime is therefore critical. Range of techniques available for sampling design. Remote sensing techniques to assess SOC are emerging based on vegetation mapping (e.g. normalised differentiated vegetation index; soil adjusted vegetation index, bare soil index, with correlation analysis). Accuracy is uncertain.
Engineered geological storage Geological CO_2 storage sites: modelling is core part of site permitting and MRV design. Both static and dynamic modelling usually prescribed in regulatory frameworks.	Range of passive and active monitoring techniques available to detect and measure subsurface CO_2 plume and surrounding domains. Seismic surveys can provide 2d and 3d images of CO_2 plume. Plume size can be correlated to measured injection mass to provide indications of C stock and storage integrity. History-matching prescribed in regulatory frameworks.
Engineered biological storage ERW: based on modelled predictions of the stoichiometric decay of calcium- and magnesium-rich silicate rocks minerals through weathering under varying environmental conditions. Biochar: decay rate of char produced from different feedstocks and under different pyrolytic conditions is providing indications to the durability of different biochar. C content can be readily measured (e.g. loss on ignition).	ERW: field trials so far proved inconclusive in detecting changes in carbonate and bicarbonate levels in field run-off following crushed rock applications. Tracers can help inform pathways, fate and behaviour of EW products. Bicohar: limited experience of field measurements of biochar. Some studies indicate negative priming effect (proposed to be the result of increased aeration and microbial activity, leading to faster breakdown of labile SOC fractions). Poor understanding of SIC cycles can impair observation due to lack of background (base-level) data.
Ocean-based CDR All mCDR methods hypothesized to date depend on model predictions of stoichiometric changes in seawater following various perturbations (e.g. alkalinity enhancement, CO_2 removal, including fertilisation and primary productivity enhancement). Ocean biogeochemical models (OBM) generally not presently considered ready for use in CDR MRV (Ho et al, 2023).	Challenging due to scale of open system. Autonomous total alkalinity (TA) passive measurements devices could hold some promise to identify effectiveness of ocean perturbation. Calibration against background alkalinity levels could support measurement of effectiveness. However, passive TA sensors not widely available. Passive CO_2 partial pressure sensors are available.

4.2.5 Non-permanence and carbon reversal

For all CDR methods, ongoing concerns remain about the durability of C stored in enhanced terrestrial C reservoirs. This residual risk is variously referred to as a 'non-permanence' or 'permanence' problem (see also Box 4-3). Carbon reversal, that is the re-emission or flux of stored C back to the atmosphere as CO_2, can occur at future points in time after an activity has received certificates or credits for achieving a given amount CDR. The issued credits may have been used to balance contemporaneous anthropogenic emissions. Thus, without a means of compensation, C reversal can compromise the environmental integrity of any issued CDR credits and impact the policies under which they function.

Box 4-3 How long is permanent?

The concept of permanence is proving to be a dynamic feature of the climate policy discourse.

Previous notions of permanence considered the benchmark to be a nominal 1,000 years, based on geological CO_2 storage. This view drew from the conclusion of the IPCC (2005), which stated that:

> "Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely [probability between 90 and 99%] to exceed 99% over 100 years and is likely [probability between 90 and 99%] to exceed 99% over 1,000 years" (IPCC 2005, SPM, p. 14). [and that] "The fraction of CO_2 stored through mineral carbonation that is retained after 1000 years is virtually certain to be 100%."

In response to these findings, governments set about introducing regulatory frameworks to ensure appropriate selection, design and management of geological CO_2 storage reservoirs commensurate with achieving 1000-year storage durability.[41]

More recently, alternative formulations have appeared. For example, a minimum storage threshold of a '500-year horizon' has been suggested by some (Ramirez Ramirez et al. 2022), albeit probably more in the context of lifecycle assessment. The EC has proposed that storage for 'several centuries' could be relevant to CDR (EU CRCF).[20]

Operators in the VCM are generally adopting 100-year or more permanence as a threshold (e.g. Puro.earth generally assumes minimum storage durations of 100 years, although has started labelling methodologies as 100+ years or 1000+ years durability). The IC-VCM Core Carbon Principles (CCP), which seeks to establish a de minimis benchmark standard for the VCM, in principle #6 state that (IC-VCM 2024):

> "The GHG emission reductions or removals from the mitigation activity shall be permanent or, where there is a risk of reversal, there shall be measures in place to address those risks and compensate reversals"

This reflects the CORSIA standard, which requires that reductions or removals be permanent or that mitigation measures are in place to monitor, mitigate, and compensate any material incidence of non-permanence (ICAO 2019).

The IC-VCM CCP assessment framework criteria (IC-VCM 2024) also states that:

> "For Categories where there is material risk [of carbon reversal]… a 40-year minimum commitment to monitor, report, and compensate for avoidable reversals, from the start date of the mitigation activity, is required."

This suggests a de facto 40-year threshold for permanence (although ambiguity remains over which categories are deemed to have a material risk, or what is considered avoidable). The general sentiment seems to imply that the 40-year threshold primarily applies to the category of activities involving biogenic reservoirs (forestry, agriculture, wetlands etc).

The risk of non-permanence relates to both:

- **Natural events.** For example, fire, pestilence, climate change induced effects in biological carbon reservoirs; seismicity, poor site selection or well failure in geological storage sites; inherent time limited storage and/or natural degradation of storage products (e.g. BC, EW); outgassing from the oceanic reservoir (e.g. due to upwelling). Notably, conversion or synthesis of bicarbonate to carbonate leads to the generation of 1 mole of CO_2 (e.g. by marine organisms, or pedagogic carbonate formation).
- **Anthropogenic events**. For example, change of management or harvesting cycles in land-based CDR systems; over-pressurising of a geological formation resulting in caprock fracturing and leakage; deliberate venting for pressure relief purposes.

[41] For example, the 2008 Victoria State Greenhouse Gas Geological Sequestration Act; the 2009 EU Directive on the geological storage of CO_2 ('the CCS Directive'); the 2011 U.S. SDWA Underground Injection Control (UIC) Class VI well rule; the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and the 1996 Protocol and the Oslo-Paris Convention on Protection of the North East Atlantic (OSPAR) risk assessment guidelines for sub-seabed geological storage of CO_2.

In either case, the likelihood, scale, and timing of any future carbon reversal is difficult to predict ex ante. This makes non-permanence a particularly vexing subject to address, generally requiring the establishment of a regime that allocates liability to compensate for any future carbon reversals over the lifespan of a CDR activity and beyond.

Ordinarily, during the active phase of removals, emissions from a carbon reversal event could be measured as activity emissions and deducted from the level of removals estimated to have occurred over a given monitoring period. However, the scale of a reversal event may exceed the quantum of measured removals within a given monitoring period[42] or occur after the phase of active removals or crediting. In these circumstances, additional liability mechanisms may be needed that oblige an entity to apply adequate redress and compensation.

Such concerns are well understood. The topic of liability and compensation for C reversal has been subject to considerable debate over the past 20 years or so in relation to both conventional CDR methods and fossil CCS. In response, several frameworks have emerged through which to address non-permanence and C reversals for credits generated in relation to C sink enhancement activities. Notably, the temporal nature of non-permanence concerns means that close interactions exist between storage durability and the duration over which credits may be issued to an activity (i.e. crediting periods; Box 4-4).

Box 4-4 Crediting periods and liability for carbon reversal

Under project-based approaches, a crediting period determines the length of time over which an activity is awarded certified credits or units. This may or may not correlate with the total amount of C removal that could occur as a result of an activity. Current VCM schemes vary between 5 years (French Label Bas Carbonne) up to 100 years (Verra/VCS forestry projects). After the end of the crediting period, the enhanced C reservoir resulting from the activity should persist and—with the exception of oceanic C reservoirs—fall within the scope of NGHGI reporting of the host country. As such, the host country takes on, de facto, the liability for any carbon reversal through ongoing NGHGI compilation and reporting and the pursuit of national GHG emission reduction and/or net zero goals (e.g. in its NDC).

Alternatively, additional post-crediting liability arrangements can be established that allocate the liability for any carbon reversal back to the activity developer. Yet, the timespans involved and the potentially ephemeral nature of activity development poses challenges for establishing such arrangements. Progress under the Article 6.4 mechanism, for example, has foundered on concerns over the lack of clarity around 'post-crediting period monitoring, reporting and remediation of reversals' (Section 2.3.2).

Under attributional/allocation approaches, no fixed crediting period would apply, and a CDR site would continue to be certified or receive credits while it was in active operation, with the site owner maintaining liability for any loss of stored C from the enhanced reservoir. This could be established as a default liability arrangement under, for example, an ETS that includes sinks and reservoirs. Therein, liability for any carbon reversal would also ultimately remain underpinned by the host country as described above (as is the case in the NZ ETS today).

Three broad approaches can be employed to address non-permanence and carbon reversal:

- **Seller liability**. In these arrangements, the activity operator maintains liability for the issued credits in the event of C reversal. If a C reversal is recorded as activity

[42] For example, 100 tCO_2 could be injected into a reservoir within a monitoring period, but 120 tCO_2 could leak out over the same period, where the additional 20 tCO_2 relates to measured removals that were credited in a previous monitoring period.

emissions during the monitoring period, these can generally be deducted from the overall level of removal credits to be issued. However, as noted previously, this may exceed the level of net removals achieved in the monitoring period. To reinforce this requirement, conditions for crediting an activity can include a mandate for the activity operator to acquire and retire credits from other suppliers or other sources where such a situation arises. Private insurance products may also be available to limit the risks for activity operators. Concerns about the cost of ex post exposure could inhibit deployment, however.

- **System level liability**. These approaches are a variant of seller liability whereby the registry operator (e.g. an ICP) puts in place measures to manage liability for carbon reversals on behalf of activity operators. This usually involves withholding a portion of the credits attributable to an activity over a monitoring period and allocating them to a **buffer account** operated by the system operator. **Tonne-year methods** can also be considered as a form of system liability (or indeed *zero-liability* for buyer, seller or system operator), since they reduce the overall level of credits issued based on non-permanence risks (Table 4-5). Alternatively, the application of **regulatory safeguards**, either within the mechanism or in broader policy frameworks, can provide assurances over the effective management of enhanced C reservoirs so as to reduce the risks of C reversal and eventually absolve the buyer or seller of liability (i.e. liability transfer). The advantage of these methods is they reduce the direct liability to the activity operator, thus reducing the disincentive to participate.
- **Buyer liability**. In these arrangements, the liability for C reversal risk is attached to the credit and therefore passed on to its acquirer. This is usually achieved through issuing **temporary credits** that must be replaced, sometimes by more permanent forms of credits, in the future upon credit expiry. This approach was adopted for A/R projects under the CDM, where only temporary CERs (tCERs) or long-term CERs (lCERs) could be issued to such activities. In this case, Kyoto Protocol Annex I country's acquiring tCERs or lCERs were required to replace them with other types of units at various points in the Kyoto Protocol implementation cycle (either CERs from other types of CDM projects, assigned amount units or other types of permanent units established under the Kyoto Protocol).

The main mechanisms considered to date for managing carbon reversal from enhanced reservoirs are summarised below (Table 4-5).

ICP registry operators in the VCM are increasingly placing the responsibility on project developers to assess the risk of non-permanence of their specific CDR activities and using this to determine the size of the buffer contribution (see buffer accounts in Table 4-5). [43]

[43] For example, the Verra Non-Permanence Risk Tools for AFOLU and Geologic Carbon Storage. Gold Standard BECCS methodology relies on the Risk Rating factor in the California Air Resources Board CCS Protocol.

Table 4-5 Mechanisms for managing carbon reversal risk in crediting approaches

Approach	Description	Examples
Seller liability	In the event that an enhanced C reservoir becomes a net emitter over a monitoring period, the activity operator is required to acquire and surrender units equal to the quantified level of emissions.	CO_2 fluxes from C reservoirs included as activity emissions in a MRV plan. Inclusion of geological CO_2 storage sites in an ETS imposes de facto seller liability (e.g. geological CO_2 storage sites in the EU are qualifying activities in the EU ETS that receive zero free allocation) Australian ERF imposes seller liability for reversals that exceed 5% of issued credits.
Buffer accounts	Withholding a portion of credits issuable to registered activities. In the event of a carbon reversal, credits from the buffer account are cancelled equal to the quantified level of emissions. Buffers can be implemented differently: ▶ Specific to each individual registered activity operator (e.g. Woodland Carbon Code) ▶ Pooled among all registered activity operators (Verra)	Widely applied to conventional CDR in the VCM. ▶ MoorFutures: 30% withheld in a buffer. ▶ Verra: 10-60% to buffer, depending on assessed risk. ▶ Woodland Carbon Code: 20% withheld in a buffer. ▶ Nori employs an "insurance pool" Verra links buffer contributions to the assessed risk made using their Non-Permanence Risk Tool (NPRT) established for AFOLU, Jurisdictional REDD+ and Geostorage activities.
Temporary credits	Issued credits must be either cancelled or renewed via monitoring at fixed future point(s) in time.	A/R under the CDM.
Tonne-year methods	Quantifies the climate benefit of temporary storage/delayed emissions based on a time-equivalency value. Approach therefore implicitly accepts the possibility of C reversal and factors this into the credit issuance process by calculating an equivalent tonne-year value of delaying atmospheric CO_2 accumulations. Several mathematical models and methods have been proposed by which to calculate tonne-year values (see IPCC 2000; s. 2.3.6.3)	So far not widely used, but interest is growing: ▶ CAR (Mexico Forest Protocol and Soil Enrichment Protocol v1.0; Canada Grasslands) ▶ Quebec MELCC (proposed) ▶ Verra (under consideration for IFM) ▶ Canada GHG Offset Credit System Regulations
Regulatory safeguards	Application of legal safeguards such as land covenants and site selection QA/QC standards and permitting to ensure appropriate selection and management of enhanced C reservoirs.	Geological storage site permitting standards (e.g. U.S. UIC Class VI well rules; EU CCS Directive) coupled to seller liability model (e.g. CO_2 storage sites included in EU ETS). 99-year covenants on land use for forestry under the NZ Permanent Forest Sink Initiative, plus liability for reversal under NZ ETS.

Third party provision of non-permanence risk coverage is also emerging as part of a suite of VCM credit coverage products being established by several firms in the insurance market (Figure 2-4; Kita & Oxbow Partners 2024).

4.3 Connecting CDR actions and Paris-aligned net zero goals

As noted in Section 4.1.2, the default policy prescriptions for CDR to date has been to view activities through the lens of activity- or project-based approaches and accounting. Yet achievement of the Paris Agreement goals will ultimately be determined by the measured emissions and removals recorded by governments in the realm of NGHGIs as compiled and reported under the UNFCCC (Section 4.1.1).

As also noted above (Section 4.1.3) the two approaches are not entirely compatible and significant asymmetries can exist across the respective MRV frames, posing some challenges for maintaining of environmental integrity:

- Firstly, NGHGIs compiled by governments to track progress against their NDCs are mostly economy-wide, encompassing all emissions and removals occurring in the territory, reported on a sectoral and managed land category basis (Box 1-2). Thereunder, if a CDR activity leads to emissions in one place (or sector or managed land category) and removals in another, assuming no import of energy or materials used in the activity, these will be recorded separately within the appropriate categories in the NGHGI. Therefore, if a government simply acquires credits from CDR activities and claims them as offsets against reported emissions, double-counting will arise (see Section 4.3.1 below).[44] Moreover, there is also the possibility that emissions and removals resulting from a specific CDR activity will *not* be effectively recorded in the NGHGI—a problem that may be referred to as 'inventory visibility' (see Section 4.3.4).
- Second, GHG emissions in some parts of the CDR activity cycle (e.g. transport, power generation, manufacturing) may already be subject to GHG emissions controls and pricing. As noted above, this poses questions about the approach to boundaries and leakage applied in project-based accounting methodologies (Section 4.2.2; Box 4-1). Furthermore, to contribute to meaningful climate mitigation, CDR methods must also not create emissions elsewhere outside the purview of NGHGI reporting (see Section 4.3.2).
- Third, at the time of writing, most credits or certificates originating from CDR activities are expected to be acquired by corporations wishing to substantiate climate-related claims (e.g. climate neutrality; see Section 2.3.1). These ambitions are leading to uncertainty as to how to distribute the accounting and claims for such actions between countries and companies (Section 4.3.3).
- Fourth, carbon reversals should also be effectively recorded in the NGHGI as emissions from the relevant sector or managed land category (Section 4.2.5; Box 4-4). This arrangement means that, in principle, liability is in place to compensate for damages to the climate system resulting from carbon reversal. Unlike project developers in the VCM, where fixed term crediting periods apply (Box 4-4), governments in essence, via their NGHGI and related reporting, retain liability in perpetuity for the risk of C reversal from

[44] In same way as for corporations acquiring credits originated from within their value chain under the VCM.

enhanced C reservoirs located in their territory.[45] Thus, as the underwriter of last resort for CDR efficacy, there is perhaps a greater imperative for governments to ensure the long-term durability of C storage than for activity developers and operators in the VCM.

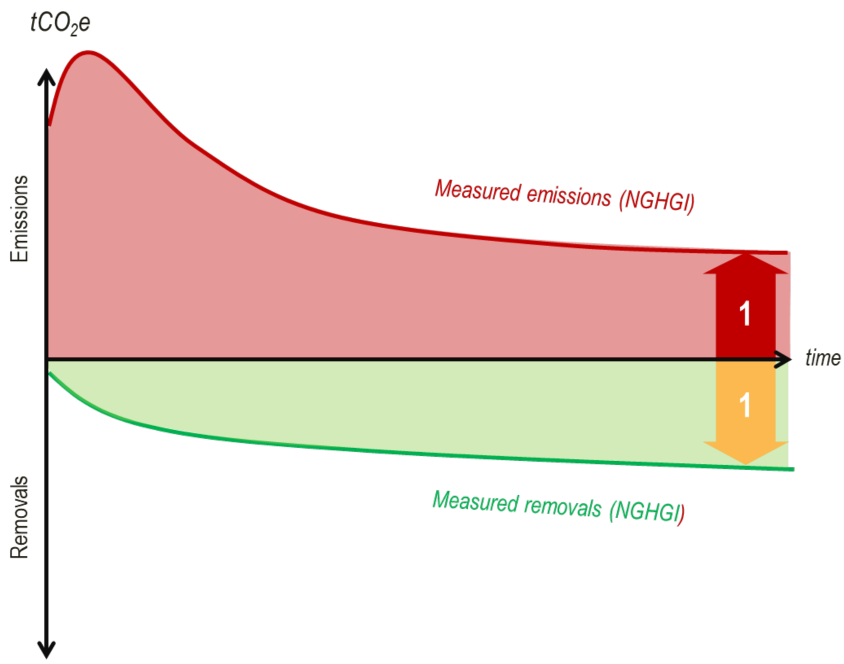
Factors affecting these connections for CDR activities are reviewed below.

4.3.1 Getting to the 'net' of net zero

For countries with net zero or climate neutrality targets in their NDCs, achieving the goal means that in the net zero target year reported GHG or CO_2 emissions must be balanced by an equivalent level of reported GHG or CO_2 removals. The instrument used for tracking this goal is their NGHGI.

This country-level net zero compliance framework is illustrated schematically below (Figure 4-7), with the ratio of emissions to removals at the point of net zero being 1:1 (i.e. in balance and therefore at *net* zero in, e.g., 2050).

Figure 4-7 Stylized depiction of emissions and removals over time to net zero



Yet the components within the wide boundaries of a project-based accounting approach that could be used to quantify and certify net removals by specific CDR activities will cut across rather than align with the NGHGI accounting sectoral framework in the following ways (Section 4.2.1; Figure 4-1):

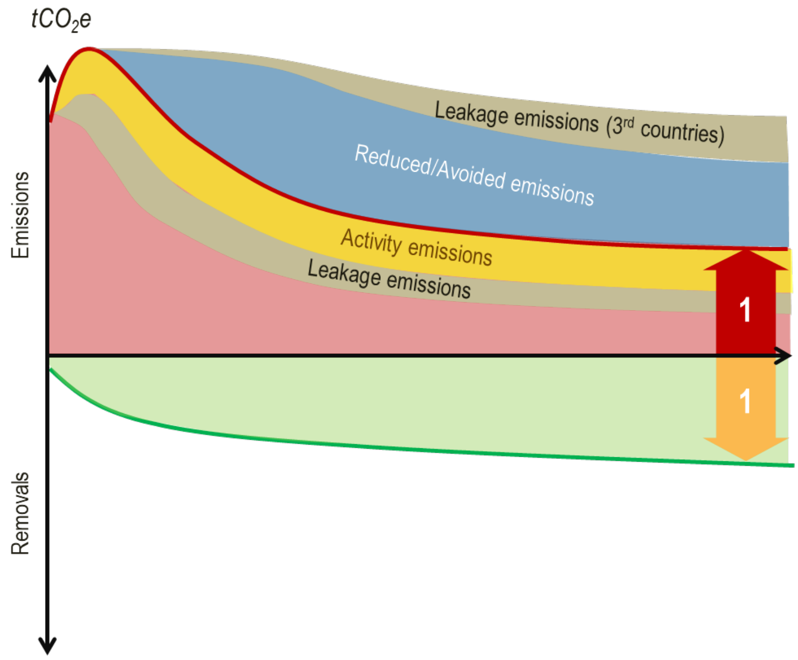
- **Measured removals** should be MRV'd nested inside of the green wedge in Figure 4-7.

[45] In some jurisdictions, the liability for carbon reversals from certain reservoirs is regulated through a permitting process that allocates remediation obligations to the private sector operator. However, in the event of operator insolvency, the government will remain the underwriter of last resort.

- **Activity emissions** should be MRV'd nested inside the red wedge in Figure 4-7, or outside where they occur in third countries in the activity supply chain (e.g. mining emissions from the supply of minerals).
- **Leakage emissions** could occur nested inside the red wedge in Figure 4-7, or outside where leakage occurs in third countries (e.g. iLUC resulting for biomass imports); and
- **Reduced/avoided emissions** are never directly recorded as an emission or removal in NGHGIs, and therefore lie entirely outside the scope of the red or green wedges in Figure 4-7 (Table 4-1).[46]

These differences are shown schematically below (Figure 4-8) relative to the stylized net zero compliance pathway illustrated above. Consequently, where project-based approaches are applied, the levels of certified net removals will not directly correlate with the measured and reported removals in NGHGIs; only a project-based attributional or allocational GHG inventory that certifies the gross removals with narrow boundaries (e.g. at a site or land parcel level) offers a straightforward means to directly align with reported removals in NGHGIs.

Figure 4-8 Stylized depiction of project-based CDR MRV components within NGHGI reports



Moreover, there are various other accounting features that influence the interconnection between project and national GHG accounts. For example, where reduced/avoided emissions are counted and certified as 'net removals' and used to offset anthropogenic emissions, an uplift in emissions could occur. In other words: emitters offsetting with certified removals that include avoided emissions will be able to emit more. While activities that arrest the ongoing

[46] Avoided emissions are reflected in national GHG inventories through reductions in reported GHG emissions.

degradation of terrestrial C pools and CO_2 fluxes from land are desirable, counting such actions as CDR will have environmental integrity implications.

As noted above, supply chain emissions attributable to a CDR activity but occurring in third countries may be counted within widely bounded, consequential, project-based net removal calculations, but would be excluded from host country's NGHGI and instead included in the NGHGI of the country of origin. This arrangement may pose accounting inconsistencies for host countries, especially where the resulting mitigation outcomes are transferred for use by third countries under Article 6 of the Paris Agreement.

Thus, attempts to align monitored removals at the project activity level with the observational data used to compile NGHGIs will face challenges, as discussed below.

4.3.2 Ensuring overall mitigation in global emissions

The Paris Agreement requires that the mechanism established under Article 6 contributes to an overall mitigation in global emissions ('OMGE'). This has so far been implemented as the cancellation of 2% of the credits issued to Article 6.4 activities. But the broader intent of OMGE can be interpreted as the avoidance of the zero-sum offsetting approach that was implemented under the Kyoto Protocol.

For CDR, OMGE poses technical considerations in respect of international leakage risks and cross-border movements of products and services. For example:

- For **DACS**, the energy source and materials inputs are critical factors affecting its efficacy and efficiency. Where energy and materials used to perform DAC are imported from third countries, the upstream GHG effects will fall outside of the host country reporting boundary. Similarly, **EW** and other **alkali-based CDR** methods are reliant on the supply of silicate-rich minerals, which in many circumstances are also likely to be imported into a host country.

  In such circumstances, a removal effect could be recorded in the host country while additional emissions accrue in another as a result of energy and materials production, extraction, processing and supply to the activity, recorded in the NGHGI of a third country.

- **BECCS** and other biomass-based CDR methods (e.g. **biochar, biomass burial**) only achieves a net CDR effect when the C stocks in the source of biomass remain in dynamic equilibrium (i.e. removals by growth are equal to the emissions assumed upon harvesting). Hence much concern is focussed on ensuring sustainable sourcing of biomass in energy policies in general, and bio-based CDR is no different. Where cross-border trade in biomass occurs, leakage risks can arise.

  Consequently, high-quality MRV of managed land in NGHGIs is essential to support BECCS operations that lead to OMGE (see Zakkour, Kemper and Dixon, 2014).

Project-based approaches with wide boundaries and lifecycle based MRV can help to address these concerns. But uncertainty persists for how these MRV approaches can dovetail with NGHGIs, and in these respects, how any cross-border effects can be reflected in NGHGIs of countries hosting CDR activities. Corresponding adjustments to national GHG accounts could help to address the accounting inconsistencies but will only apply where the country hosting the CDR activity elects to transfer the mitigation outcome to a third country.

As noted above (Section 2.4.1), the development of integrated assessments including a wider range of CDR methods could help to reveal further information about the cross-sectoral effects that can arise from deployment of a portfolio of CDR methods.

4.3.3 Voluntary climate action, GHG accounting and climate-related claims

A number of corporations, including Microsoft, Stripe, Shopify and Swiss Re etc are implementing extensive CDR credit/certificate procurement programmes in ongoing efforts to substantiate voluntary corporate climate neutrality claims (Box 1-1; Table 2-1). These endeavours are, however, posing vexing new questions for climate policy design, in particular, the relationship of these targets with country-level GHG targets, inventories, accounting, reporting and claims.

The established notion is that the emissions of firms primarily occur within national territorial boundaries meaning that they are, at least in principle, 'nested' within the NGHGI(s) of the country(ies) within which they operate (i.e. a firm's GHG emissions are subset of a country's GHG emissions, international aviation and maritime emissions excepted; see Section 4.1.1). The corollary of this arrangement is that when companies implement or support actions to reduce emissions and/or remove carbon, the mitigation outcomes should be simultaneously and seamlessly reflected in both corporate GHGIs and NGHGIs (subject to inventory visibility; Section 4.3.4). As such, hosted corporate actions also get recorded as country action.

Challenging this view is the assertion by some stakeholders that claims linked to certified mitigation outcomes (including from CDR) can only be made by a company or a country, but not by both. Under such an arrangement, if a company acquires and cancels CDR credits/ certificates towards a climate neutrality claim, the country hosting the CDR activity must *not* count that same mitigation when tracking progress towards its NDC (Salway and Streck 2021; Ahonen et al. 2022; Salway 2023; Fearnehough et al. 2023; Stoefs 2024).

Proponents suggest that, where host countries are *not* making an accounting adjustment, the credit acquirer must limit their claim to what is variably termed 'finance-based', 'contribution', 'mitigation contribution', or 'climate contribution' based claims as opposed to 'offsetting' claims (or compensation or neutralisation). The reasoning takes the view that a double claim by a country and a company casts doubt upon any offset claim by the company (Salway and Streck 2021), and that the limitation on contribution claims help to reinforce the idea that offsetting should not replace measures by companies to reduce their own emissions (e.g. Fearnehough et al. 2023). To date, proponents have not clarified whether the approach applies to all types of mitigation outcomes, or just emission reductions. However, Stoefs (2024) makes such observations in direct reference to the EU's CRCF.

Thus, for these stakeholders, high integrity corporate claims established through the VCM require corresponding adjustments in the same way as international transfers of mitigation outcomes under Article 6 of the Paris Agreement (Box 4-5). Otherwise, the claim must be limited to a 'contribution' type as outlined above.

Box 4-5 Article 6 – ensuring the environmental integrity of mitigation outcomes

The Paris Agreement's Article 6 supports cooperation between signatory Parties including through the trading of mitigation outcomes (internationally transferred mitigation outcomes or "ITMOs"). Where a Paris Agreement country Party hosts a mitigation action, it may authorize the resulting mitigation outcome as ITMOs either for use by another Party, who may count the acquired credits towards its own NDC, or for use for other international mitigation purposes (OIMP; e.g. CORSIA). In providing an ITMO authorisation, the host party waives its right to claim the same mitigation outcome against its own NDC, as all ITMOs are subject to 'corresponding adjustments'. Corresponding adjustments means that, when accounting for progress against NDCs, host Party's must add back on the equivalent emissions of all authorized ITMOs occurring with an NDC period, and the acquiring Party's can deduct them in its NDC accounting. The adjustment avoids double counting of the same mitigation outcome by two countries in respect of their NDCs, or the host country towards its NDC plus OIMP.

Negotiations under the UNFCCC have more recently considered the origination of *unauthorized* credits from the UN's centralized Article 6.4 mechanism. Since no authorization is provided, no corresponding adjustment would be applied by the host country Party, casting doubt upon the environmental integrity of the resulting credits. To limit environmental integrity risks, the use cases for such credits will be limited to the cases exemplified by the UNFCCC in a 2022 decision at the Sharm El-Sheikh Climate Conference:

> "The mechanism registry shall track…A6.4ERs not specified as authorized for use towards achievement of NDCs and/or for other international mitigation purposes (mitigation contribution A6.4ERs), which may be used, inter alia, for results-based climate finance, domestic mitigation pricing schemes or domestic price-based measures, for the purpose of contributing to the reduction of emission levels in the host Party." (UNFCCC 2022, Decision 7/CMA.4; Annex I, para 29).

Countries therefore wishing to establish domestic carbon crediting systems but lacking the infrastructure to do so could instead adopt 'mitigation contribution A6.4ERs' as a domestic trading unit. Although this and other UNFCCC decisions relating to Article 6.2 also refer to the registry functions needed for ITMOs used for 'voluntary cancellation' purposes, there is no explicit mention of applying corresponding adjustments to credits originated through ICPs and cancelled in pursuit of voluntary corporate claims.

The UNFCCC language around 'mitigation contribution 6.4ERs' is, however, being interpreted by some stakeholders as supporting a limitation on the types of claims that may be applied for all unauthorised carbon credits acquired in the VCM. The reasoning is that, without a corresponding adjustment, payments for any unauthorized credits can only contribute towards mitigation actions of the host country; ergo, entities acquiring any unauthorised credits are only entitled to make 'mitigation contribution' rather than an 'offsetting' claims (e.g. Crook 2022).

The proposal for corporate 'contribution claims' poses a number of issues, however, which can impact upon climate policymaking and the tracking and accounting of climate mitigation.

Firstly, eliminating the concept of nested GHG inventories in order to eradicate double claiming in essence places corporate and country GHG accounts on an equal footing in respect of the Paris Agreement. But companies are not signatories to the Paris Agreement and do not have corporate NDCs. Also, the approach is inconsistent with the way in which public policy has traditionally sought to leverage private finance into climate action. Such nested arrangements were an important feature of the Kyoto Protocol where private sector actors were allowed to acquire certified emissions reductions (CERs) from the CDM and subsequently surrender them to national authorities under national PAMs (e.g. in both the EU and Japan, among others). In the EU, this was through the linkage of CERs as compliance units in Phase II of the EU ETS.

Following the same principle, Article 6 of the Paris Agreement requires countries to apply corresponding adjustments only when counting ITMOs towards NDCs or OIMP (Box 4-5). So unless the voluntary buyers surrender the credits to the national authorities in their country of incorporation (or transfer them for cancellation for OIMP), it seems unclear why a corresponding adjustment is needed; these corporate targets, being voluntary in nature, are being pursued entirely irrespective of whether their country of incorporation also wishes to acquire CDR certificates to count towards their NDC. Under this arrangement, the voluntary nature of the climate-related action allows for a claim, whereas a compliance related action would not usually support any corporate climate-related claim. As such, if the country of incorporation of the buyer does not intend or wish to transact under Article 6, or use national PAMs to devolve the acquisition to the private sector, the VCM would seemingly act to enhance mitigation ambition by supporting actions that would otherwise not occur if left solely to governments through Article 6. Thus, the corollary is that if countries do allow or oblige national corporate operators to acquire carbon credits, these should be surrendered to a national authority as ITMOs and corresponding adjustments applied accordingly and no claims would be made by the firm due to the compliance-driven nature of the action.

Moreover, it remains uncertain what accounting should be applied if the country of incorporation of the firm making the voluntary claim *and* the host country of the activity are one and the same: would the host country still be required to make an adjustment to its national accounts based on the voluntary actions of a national company taking place only within its territorial borders? A result of this confluence is that, if certificates or credits acquired in pursuit of corporate mitigation action are to be exclusively counted against corporate GHGIs, and nationally supported mitigation actions exclusively against NGHGIs, neither countries nor companies will be able to simultaneously account for and report (or 'claim') to have achieved net zero.[47]

Drawing upon the perspective of nested carbon accounts, counter views have instead proposed the idea of 'dual accounting' and 'co-claiming'. Dual accounting describes a situation of parallel accounts where emissions and removals count once against the GHG inventory of the private entity that purchases removals and once against the NGHGI of the country where the CDR occurred. Co-claiming means both private and public actors can 'claim' the mitigation outcome in parallel because of the dual accounts (e.g. Burbridge et al. 2024; Microsoft 2024).

Temporal aspects can, however, be an additional source of complexity. In some cases corporate targets aims to neutralise historical emissions (e.g. Microsoft; Smith 2020), meaning that the corporate accounting of CDR certificates/credits takes place against emissions that

[47] Although Salway and Streck (2021) note that this mainly relates to the claims, and that "such double claiming would not affect greenhouse gas accounting under the Paris Agreement".

occurred in the past and have already been counted in NGHGIs, rather than contemporaneous emissions that will be counted by countries against their current NDCs.

In summary, at the time of writing, the legal, spatial and temporal nature of accounting and claims remains subject to significant debate and can be expected to continue evolving over coming years.

4.3.4 Understanding inventory visibility

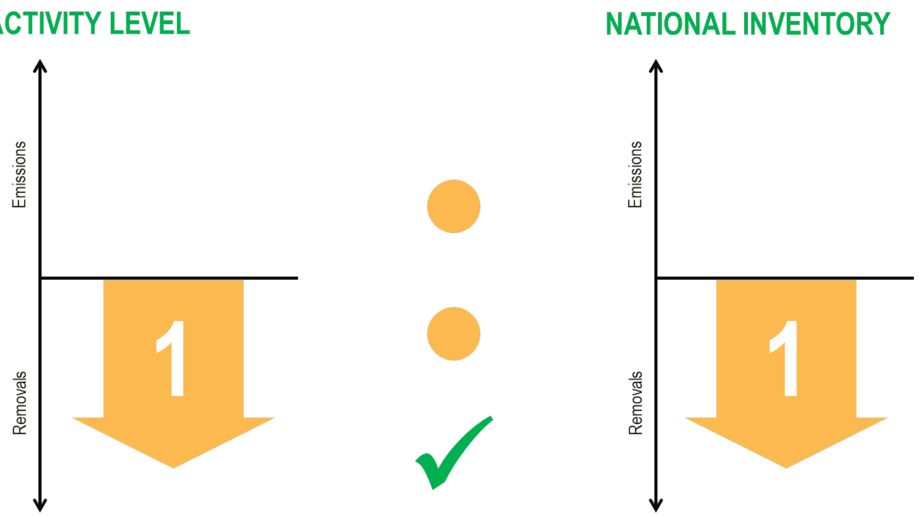
Drawing on the discussion around claims, in addition to creating certified credits for various end uses (e.g. corporate 'neutralisation' claims), a CDR activity should also produce a parallel measurable GHG effect in the host country NGHGI. This 'dual accounting' effect is essential for any domestic CDR certification scheme to have any political utility. In other words: where a CDR activity is incentivised and credited in a country, the activity should also be working towards achieving the common aims of both the host country and the credit acquirer (especially where corresponding adjustments will be applied).

However, as noted above, there are differing views on how the accounting and claims could work, and there are also fundamental differences in the way consequential and attributional/allocation project-based approaches work in practice. The latter can lead to asymmetries between the two sets of accounts.

Moreover, as noted by Prag et al. (2013), Zakkour et al. (2022) and Schneider et al. (2022), there are challenges to connecting GHG effects at the project activity level and the national level. The degree of connectivity between the granular MRV at the activity level and the MRV applied at the national has been termed 'inventory visibility' (Schneider et al.; 2022). Yet many differences exist in the MRV applied between the two, which will inevitably produce mismatches.

The idealised situation for MRV and accounting is where measured removals at an activity level are fully aligned with the reported removals in the host country's NGHGI (i.e. matched at a ratio of 1:1; Figure 4-9).

Figure 4-9 Activity and national level accounting for CDR methods where reported removals align

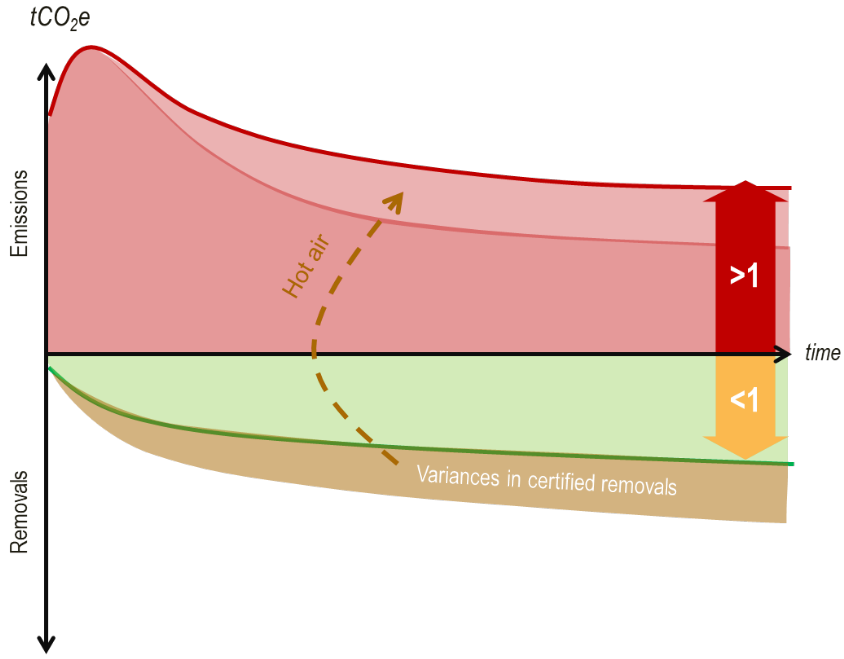


Under this arrangement, crediting or certification of CDR activities will clearly drive a parallel, symmetrical, measurable effect in the tracking system used to measure progress towards the host country's climate targets. Problematically, any outcome other than a symmetrical 1:1 alignment as shown above will drive environmental integrity concerns. This issue arises in both directions:

- If a removal effect is MRV'd and recorded at the activity level but only partially recorded or entirely excluded from the NGHGI, resulting credits could present environmental integrity and policy coherence issues. If the credits are used to support neutralisation claims, entities within a jurisdiction could claim climate neutrality based on actions that the host country could not, despite the activity being located in their territory.
- If host country's MRV approach records a removal in a NGHGI that is not measurable at the activity level, the integrity of the country NGHGI and accounting may be questioned. Accusations could arise that countries are using accounting 'tricks' to allow higher emissions under net zero accounting, which can be equated to a form of "hot air" (Figure 4-10).

Thus, any asymmetry will cast doubt, either real or perceived, upon the veracity of the measured and certified removals and/or the associated levels of recorded removals being reported in pursuit of national targets (e.g. net zero goals).

Figure 4-10 The effect on net zero goals when certified removals include hot air



There are a number of factors that will influence the degree to which symmetry and alignment is achieved:

- Firstly, discrepancies will clearly occur where emission reductions are counted as certifiable 'removals', as described above.
- Second, applying the principle of conservativeness in activity level measurements, or applying discount factors to adjust for any uncertainty, will also reduce the level of removals that could be credited at the activity level.
- Third, there are differences in the way NGHGI compilation methods apply to different types of CDR methods, which will variably impact upon alignment of the accounts. The significance of these effects is considered in more detail below.

In respect of the third item, the current coverage of IPCC GHG inventory guidance for various CDR methods is summarised below (Table 4-6). Notably, to aid comparison, the summary table uses the same CDR method categories as used above to assess the protocols available in the VCM (Table 2-2). The coverage for different CDR methods is summarised below.

Table 4-6 Coverage of CDR methods in current IPCC NGHGI Guidelines

CDR method	Coverage	Applicable sections / comments	Publication
BECCS	✓	Volume 2:2 (Stationary combustion, Tier 3) Volume 3 (Various industrial sources, Tier 3 only) Volume 2:5 (CO_2 Transport and Storage, Tier 3 only)	2006 GLs
DACS + geostorage	~	Volume 2:5 (CO_2 Transport and Storage)	2006 GLs
DACS + mineral storage	✗	[explicitly excluded in Vol 2, Chapter 5]	2006 GLs
Enhanced weathering	~ / ✗	Volume 4:2.3.3.1 (advises Tier 3 approaches for soil inorganic carbon fluxes) [Freshwater and oceanic GHG fluxes not measured and reported]	2006 GLs
Biochar	~	Volume 1 (new guidance for mineral soils) Volume 4 (Biochar amendments to soil + Appendix 4)	2019 Refinement
Bio-oil storage	✗	[Parties could propose own methodology (probably Tier 3)]	n/a
Biomass burial	✗	[Parties could propose own methodology (probably Tier 3)]	n/a
Biomass sinking	✗	[Freshwater GHG fluxes not measured and reported in NGHGIs]	n/a
Ocean alkalinity enhancement	✗	[Oceanic GHG fluxes not measured and reported in NGHGIs]	n/a

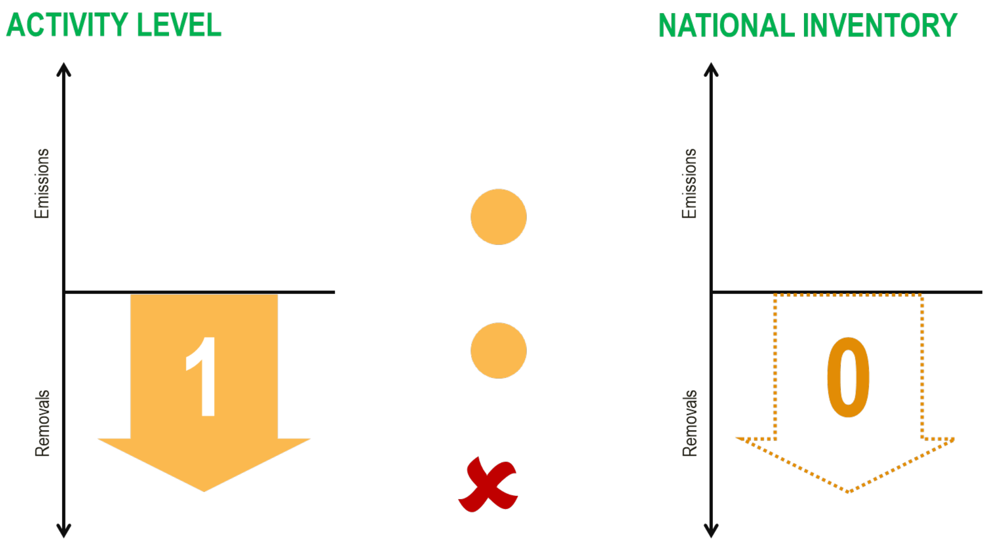
Novel (engineered) CDR methods

For CDR activities involving engineered geological CO_2 storage, the recorded removals at the activity level and in NGHGI reports should, in principle, be symmetrical. NGHGI compilation guidelines (i.e. IPCC 2006) require Tier 3 methods to be applied to both fossil and biogenic CO_2 capture, transport, and geological CO_2 storage. This means that measured removals/emissions at the activity level by a BECCS project site, for example, will also be directly used for the compilation of NGHGIs (as in Figure 4-9):[48] the CO_2 removal is recorded at the site of CO_2 capture (e.g. in the Energy sector in the NGHGI), and any subsequent emission of the captured CO_2 during transport or storage is recorded as an emission in the same way as fossil CO_2 (also in the Energy sector in the NGHGI).

Conversely, the absence of IPCC methodological guidance for some novel CDR methods—primarily: DACS, EW, mCDR, bio-oil injection, biomass burial, and to an extent, biochar—may mean that any removals from such activities may be entirely excluded from NGHGI records (Figure 4-11).

[48] A tier represents a level of methodological complexity. Usually three tiers are provided. Tier 1 is the basic method, Tier 2 intermediate and Tier 3 most demanding in terms of complexity and data requirements. Tier 3 usually requires the use of specific activity level MRV data within the NGHGI. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate. (IPCC 2006)

Figure 4-11 Activity and national level accounting for solutions where IPCC guidance is absent



Nonetheless, where IPCC guidance is entirely absent, alignment can be achieved by incorporating measured removals at the activity level directly into the host country's NGHGI (Box 4-6). In essence, this would mirror the Tier 3 approach described for BECCS (i.e. the absence of specific reporting categories would mean that the recorded removals would need to be noted as 'Other' memo items in the relevant NGHGI). The lessons-learned could be used to support future refinements to IPCC Guidelines.

Issues may also arise for alignment of recorded removal for biochar at the activity and NGHGI level due to partial 'visibility'. Provisional guidance on the treatment of biochar in NGHGIs (IPCC 2019) proposes that the C content of biochar be recorded as an addition to soil C pool in the AFOLU sector of NGHGIs. The corollary is that when the biomass used to make the biochar was harvested, it was recorded as an emission in the AFOLU sector of a NGHGI. Thus, a C stock transfer firstly out of, and then into, the AFOLU sector is recorded in the NGHGI. Differences between the two are recorded as an emission in the AFOLU account. Consequently, unlike BECCS, the biochar production site is not technically recorded as a CDR activity in the NGHGI. On the other hand, VCM biochar methodologies in the VCM have so far tended to record the removal at the point of biochar production rather than at the point of its application to land. Only the latter would be consistent with IPCC guidance.

Furthermore, the IPCC (2019) method for biochar proposes default factors for the 'fraction of biochar carbon remaining in soil 100 years after application', ranging from 0.65 to 0.89 (Table 3-4). On this basis, 11 to 35% of the C stored in biochar can be assumed to be emitted over a 100-year period. The approach infers the possible use of a first order decay model to support NGHGI compilation in a similar way to that applied to the HWP C pool. Therefore, in order to align the activity level MRV with NGHGIs, similar decay rates might need to be factored into the methodologies applied at the activity level. Such an approach may also call for alternative methods for managing permanence (e.g. tonne year methods that take account of the temporary nature of the measured removal effect). Cross-border movements of biochar could also pose OMGE issues (Section 4.3.2).

CDR methods such as bio-oil injection could potentially mirror BECCS, while biomass burial will face similar challenges to biochar.

Box 4-6 Inventory invisible – the case of DACS and ocean-based CDR

The absence of specific IPCC guidance has sparked a debate about how DACS could be recorded in NGHGIs. A key question in these respects is: where will the measured removals be allocated?

The most obvious approach is to record the mass of CO_2 removed by DACS in the NGHGI of the country where the DAC plant is sited. Any emissions downstream of the DAC plant would be recorded in accordance with Volume 2, Chapter 5 of IPCC 2006 covering the transport and geological storage of CO_2. Such an approach could eventually be formalised in IPCC Guidance, but interim approaches are also possible. For example, Norway's NGHGI took account of the emission reductions achieved by the Sleipner CCS project since 1996, around 10 years before IPCC guidance for CO_2 transport and storage existed. The country unilaterally elected to not report the CO_2 processing emissions that were instead captured (i.e. not reported under IPCC reporting category 1.B.2.a.ii – venting and flaring), but otherwise reported the amount of CO_2 captured and injected as a memo (other) item. Norway's NGHGI reports also provided significant details on the methods employed to trace the injected CO_2 so as to provide assurances over the validity of the non-reported emissions. The approach was considered acceptable under the UNFCCC's international assessment and review process.

Under the Paris Agreement, Guidance on information to facilitate clarity, transparency and understanding of NDCs (ICTU; Decision 4/CMA.1) states that: "Parties whose NDC cannot be accounted for using methodologies covered by IPCC guidelines provide information on their own methodology used…" and also that "…once a source, sink or activity is included, continue to include it".

Conversely, most mCDR methods do not present any obvious means by which to allocate CO_2 drawdown to a country (outside of territorial waters, if such an effect can be delineated accordingly). If mCDR were to receive widespread support, it would likely need to operate under a separate credit/certification system operated by an international institution such as the International Maritime Organisation. Issued removal credits could be acquired by countries and counted towards climate goals (including devolving the acquisition to the private sector). Issues relating to OMGE in respect of input energy and materials applied in the mCDR method, and carbon reversals in respect of liability for any CO_2 outgassing, requires further consideration, however.

To address the potential gaps in NGHGI coverage for CDR methods, the IPCC Panel agreed that—under the auspices of the Task Force on National Greenhouse Gas Inventories (TFI)—the seventh assessment cycle will include an Expert Meeting on Carbon Dioxide Removal Technologies and Carbon Capture Utilization and Storage and provide a Methodology Report on these by the end of 2027 (IPCC 2024). An Expert Meeting is scheduled for 1-3 July 2024.

Conventional (nature based) CDR methods

Presently, there are wide variations in the factors used by countries in compiling AFOLU sector NGHGIs, including:

- **Land use categories**. AFOLU inventories consist of six different land categories covering: Forest land, Cropland, Grassland, Wetland, Settlements, and Other Land. In addition, NGHGIs need to separately account for land undergoing Land Conversion (i.e. a change from one category to another) for a 20-year period following conversion. Different approaches and datasets may be applied to different land categories.

- **Carbon pools**. Six different carbon pools are be considered within each land use category: aboveground and belowground biomass; litter and deadwood (which are often aggregated to a dead organic matter pool in some land use categories), mineral and organic soils. Under certain conditions, C stock changes in C pools can be assumed in equilibrium under the Tier 1 assumption, otherwise, the C stock changes have to be reported for all pools if existing in the category. In addition there is a HWP pool that is split into sawn wood, wood panels and paper and paperboard, and reported as a separate category within NGHGIs.
- **Activity data**. In general, three different approaches are distinguished for activity data (i.e. the AFOLU areas subject to different management techniques):
  - ↳ Approach 1 includes the total land use area, where no land use change data is available.
  - ↳ Approach 2 includes the total land use area as well as the land use changes between the categories.
  - ↳ Approach 3 uses spatially explicit land use conversion data that is available (e.g. from maps, remote sensing or fixed grid inventories).

  Depending on the available data, NGHGI compilers usually combine several approaches to obtain the national managed land use matrix (termed 'stratification'). In addition, countries may further stratify the land use categories by other factors (e.g. ecoregion, soil types, vegetation types, etc), which also has an impact on the selection of the Methods and the tier of approach applied.
- **Methods**. Either stock-change methods or gain-loss methods may be applied to some land categories and C pools therein. Depending on the available data and if the category and pool are significant, different methodological tiers can be applied to estimate C stock changes in a given C pool:
  - ↳ *Tier 1* involves the use of default factors (often 'no change');
  - ↳ *Tier 2* involves use of country-specific factors;
  - ↳ *Tier 3* consists of more complex dedicated methods (e.g. national models of the land category and C pools).

  However, compared to other NGHGI sectors, clear differentiation between the tiers in the AFOLU sector can be difficult because countries may mix default and country specific factors to calculate a certain pool.

The number of pools and variety of methods requires the combination of several different datasets and offers latitude for variations and uncertainties to arise within NGHGIs. Aggregate uncertainty at the national level is often higher than 20%. For example, in a recent NGHGI report, the EU estimates aggregate uncertainty in its LULUCF sector data to be 39.9%, compared to 2.6% in fuel combustion and 24.7% in agriculture (European Environment Agency 2023, Table 1.16).

Notably, the same or similar components and methods established in IPCC guidelines are also widely used to estimate C stock changes in project level certification programmes applicable to conventional CDR methods (e.g. Label bas carbone). Methods therein typically include the use of look up tables and/or software tools that incorporate IPCC default factors and other variables to estimate C stocks. Such arrangements can imply alignment between activity level and NGHGI accounts. However, small differences in one or two assumptions or default factors can potentially lead to wide differences in the estimated level of CDR at the respective levels. Furthermore, application of direct measurement (surveys, sampling, remote sensing etc) at either or both activity and NGHGI levels is likely to drive further discrepancies in accounts (unless the surveys are unified).

Some example scenarios under where discrepancies may arise and their effect on the idealised '1:1 ratio' match between project and national level accounts are summarised below (Table 4-7).

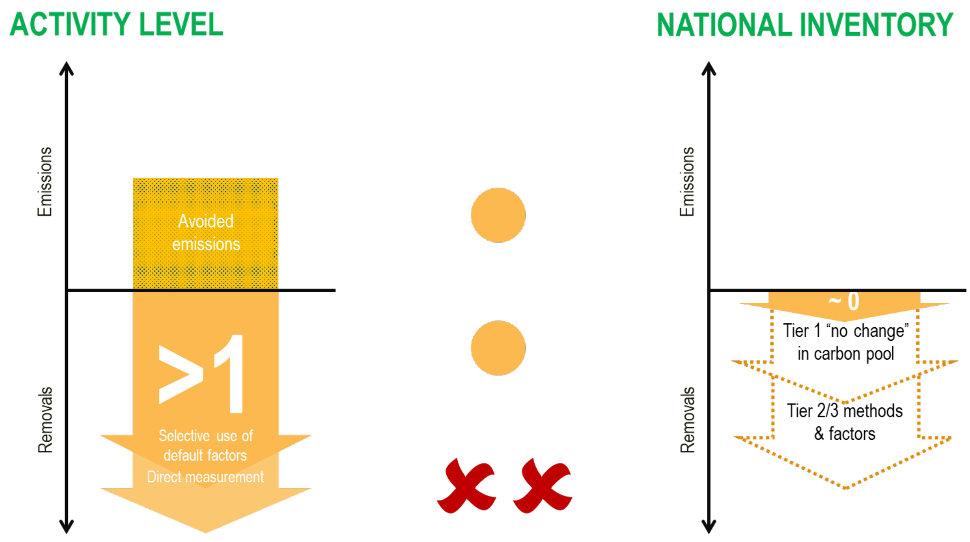
Table 4-7 Scenarios driving inventory visibility challenges

MRV approach		Activity Level[1]	NGHGI Level[1]
Direct measurement differences	Directly measured activity level removals may exceed default factors used for NGHGI compilation	>1	1
	Directly measured activity level removals may be lower (or zero) compared to default factors used in the NGHGI	~0 to 1	>1
Omission	Default factors applied to some C pools may be excluded or assume "no change" under Tier 1 methods in NGHGI compilation, whereas C stock changes in the C pool may be estimated at the activity level	>0	0
Overstatement	Default factors applied to some C pools at the activity level could overstate removals compared to the selected default factor used for NGHGI compilation	>1	1
Mismatches	Default factors applied at the activity level could be significantly different to Tier 1, 2 or 3 factors used for NGHGI compilation in the relevant C pool	<>1	<>1

Note: (1) the estimates here relate to the scope for and direction of deviation away from the 'true' value of 1 in both the project and NGHGI accounts.

Some potential discrepancies that could impact upon the inventory visibility of conventional (nature based) CDR are summarised schematically below (Figure 4-12).

Figure 4-12 Activity and national level accounting for solutions where different assumptions are made



As shown above (Figure 4-12), various combinations of scenarios and factors driving discrepancies could occur simultaneously leading to potentially significant asymmetries that undermine inventory visibility in several different ways.

The range of aggregate uncertainties and potential outcomes that can occur from small differences between the MRV applied at the different levels are potentially large and difficult to quantify.

Reconciling activity- and national-level GHG accounts

Based on the analysis above, strong, symmetrical, alignment between certified activity level removals and recorded removals at the NGHGI level is desirable but challenging to achieve, especially for conventional CDR.

As noted in Zakkour et al. (2022) and McDonald et al. (2023), steps may be taken to resolve discrepancies, enhance symmetry, and improve inventory visibility in a coherent manner, including:

1. **Aligning methods**. For biological capture and storage: further steps to harmonise methods at activity level may be possible (e.g. better integration of the same data sets used at the activity level into those applied in NGHGI compilation; see Box 4-7).
2. **Aligning outcomes**. There may be possibilities for host countries to make 'internal adjustments' to their NGHGIs based on measured and certified removals occurring at the project level. In these respects:
    a. For engineered geological storage activities, this should be a given because of the requirement to apply Tier 3 methods in NGHGI compilation, as described above.

b. For biological capture and storage, complications will arise because of the way in which NGHGIs are compiled. The simple carve out and replacement of estimated emissions and removals data for specific parcels of land in the NGHGI with the data derived from activity level certification is unlikely to be straightforward. Typically, C stock changes within the C pools in some land categories, as well as in converted land categories, are either assumed as 'no change' or calculated at the national level (rather than each land parcel) based on longer term linear extrapolations from which year-on-year national C stock change estimates in the given land category are derived.
c. For other CDR methods, a case-by-case approach may be possible. Challenges remain to be addressed for biochar, however.

3. **Managing claims**. Where strong asymmetry and inventory 'invisibility' problems cannot be readily resolved, it may be necessary for policymakers to consider restricting the types of claims made against certificates or credits acquired for neutralisation purposes.

The IPCC (2019) also suggests some ways by which alignment and symmetry could be approached in the LULUCF sector (see Box 4-7).

Box 4-7 IPCC 2019 Guidance on LULUCF project and NGHGI alignment

IPCC (2019) Box 2.0A in Volume 4, Chapter 2, sets out suggestions for "Consistency Between AFOLU Projects or Activities and IPCC Inventory Guidelines". Among others, the guidance therein suggests that when using IPCC guidelines for projects and activities the following steps should be considered:

i) Define the spatial boundaries of the territory impacted by the activity;
ii) Identify the land-use categories and subcategories of the NGHGI impacted by the activity.
iii) Identify pools and gases impacted by the activity;
iv) Identify the time frame (temporal boundaries) of the activity and ensure full reporting of any legacy emissions and removals associated with it;
v) Develop estimates by applying methods consistent with IPCC guidance, so ensuring
vi) consistency among the results of activities and the trends of times series of relevant NGHGI categories.

Conversely, it notes that when using data collected from activities and projects for improving or evaluating information and estimates reported in the NGHGI, it is important to:

i) Define and report the reference conditions (e.g., climate, soil, management system) for which the data from the activity or project are valid and how it could be used in the NGHGI compilation.
ii) Determine if the activity or emissions factor data in the project are representative of the national average and, if not, apply methods that ensure the NGHGI is not biased by them, e.g., limiting the use of the data to the land subject to the activity or project only and modifying the data used in the NGHGI to prevent bias.
iii) Define and report the level of variability (heterogeneity) of the data.
iv) Ensure the data is available and consistently applied for the entire time series.

4.3.5 Implementing redress for carbon reversals

The VCM market to date has sought to address carbon reversals through the application of project-based risk assessments covering factors such as natural events, management approaches, and financial, political, and regulatory aspects etc (Section 4.2.5). Results of the assessment is used to inform matters such as the size of a buffer to be withheld (Table 4-5).

Commensurate with the privately-run nature of the VCM, the approach tends to be passive and reactive, rather than driving more proactive, upfront, approaches to risk management and control that could be delivered through government regulation. With the exception of geological CO_2 storage, far less attention has been afforded to the potential upfront safeguards and oversight that could be applied to provide quality assurance and quality control (QA/QC) over secure C storage in enhanced reservoirs. Such regulatory approaches have, however, been key to underpinning non-permanence risks associated with the inclusion of CCS in carbon markets (Table 4-5).

Moreover, any CO_2 fluxes resulting from the depletion of enhanced C reservoirs will need to be effectively recorded in host country NGHGIs and counted against NDC targets of the host (see Box 4-6 in respect of ICTU). This linkage is essential if the current momentum in the CDR space is to be maintained. A key consideration moving forward therefore is whether countries hosting CDR activities are ready, willing and able to take on responsibility for the MRV of hosted enhanced C reservoirs and accept the liability for any carbon reversals therefrom, especially over the longer-term. These responsibilities may call for a change in emphasis away from more passive risk assessment towards a discourse around the need for more upfront QA/QC arrangements that allow the host to better control such risks.

The ongoing dialogue on the treatment of removals under the Article 6.4 mechanism could offer greater insight into government perspectives in these regards. Capacity building work under, for example, the Article 6 Partnership could also help to prepare host countries for hosting enhanced C sinks and reservoirs.

4.4 Clustering CDR 'MRV-ability'

Based on the analysis and discussion presented above, a rapid assessment of CDR MRV-ability has been undertaken. The evaluation was based around several key criteria as summarised below (Table 4-8).

Table 4-8 MRV-ability assessment elements

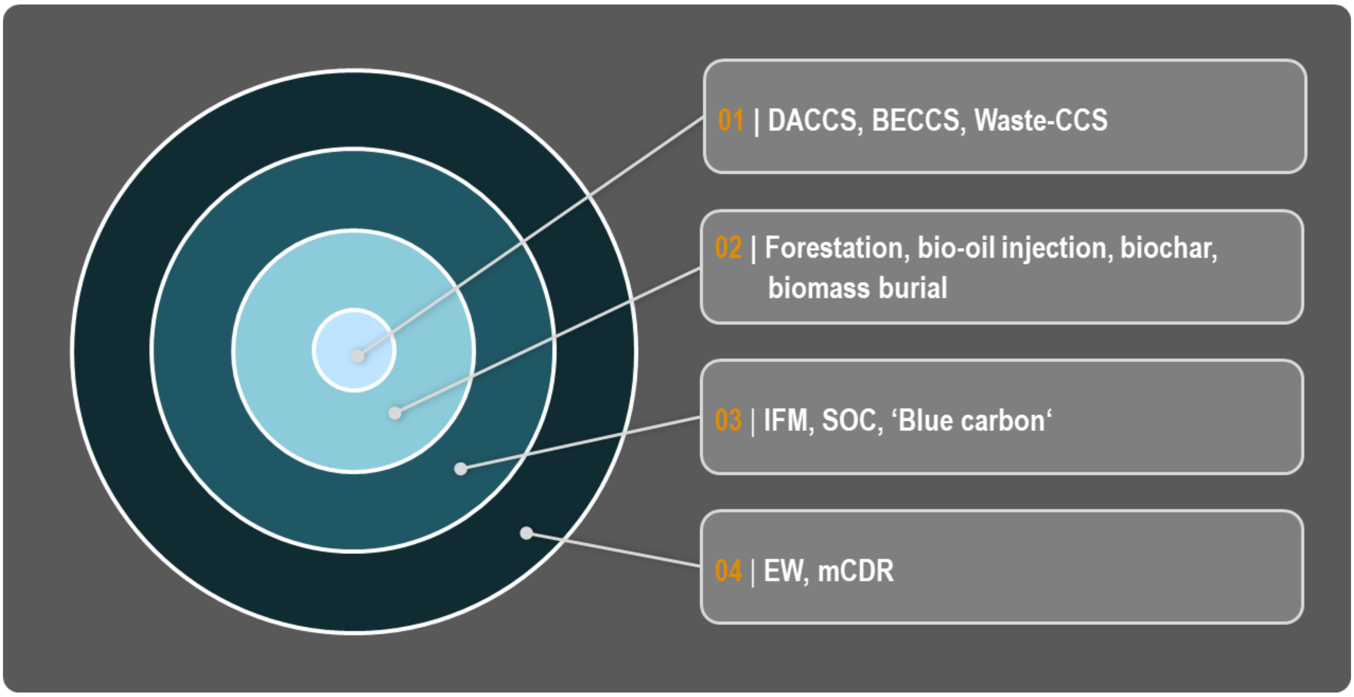
Element	Criteria
Boundaries & Leakage	▶ Can the CDR system boundary be readily defined? ▶ Is there clarity over how different emission sources and/or C pools should be treated? ▶ Are leakage risks identifiable and measurable?
Baselines & Additionality	▶ Can baselines be established and measured in a comprehensive manner? ▶ Is project additionality relevant and measurable? ▶ What is the risk of adverse selection or uneven additionality assessment?
Monitoring & Verification	▶ Can the capture and storage of CO_2 be directly observed and monitored? ▶ What levels of uncertainty can be achieved in monitoring the CDR effect? For which C pools? ▶ How significant is the CDR effect compared to other aspects impacting GHG effects (e.g. emissions avoidance)?
Non-permanence	▶ What is the risk of non-permanence of the removal effect? ▶ Can the risk of carbon reversal be managed to a tolerable level? ▶ Can the liability for ongoing storage/reversals be effectively assigned to a single party?
Accounting	▶ Is there a risk of double rewarding or double counting the GHG emission reductions/removals effect? ▶ Will the measured CDR effect at the activity level be integrated and aligned with NGHGIs?

The results from evaluation are clustered into four categories:

- **Category 1 – Core, proven, CDR activities**. CDR methods falling within this MRV category can be readily integrated into climate policies, including associated carbon markets and accounting frameworks. The focus here is on engineered geological CO_2 storage solutions, especially BECCS and DACS, drawing from long-standing regulatory and accounting frameworks established for CCS, the relative ease by which CO_2 flows can measured and the exitance of liability frameworks to assign liability to compensate for carbon reversals.
- **Category 2 – Known challenges**. CDR methods falling in this category face some known challenges, but could be integrated climate policy, carbon markets and accounting frameworks with some straightforward adjustments. These may include, for example, the boundary in respect of the scope of MRV requirements (e.g. in the case of forestation, focusing activity level MRV on aboveground biomass only) or accounting in terms of adjustments NGHGI compilation methods (e.g. to better align biochar inclusion). Methods such as biomass burial and bio-oil injection may also fall into this category.
- **Category 3 – Major challenges**. CDR methods in this category must overcome major MRV hurdles before integration into mainstream climate policy approaches. The challenges include additionality (e.g. IFM), measurement (SOC enhancement) and durability (SOC enhancement).
- **Category 4 – Significant barriers**. This category includes CDR methods which face major monitoring barriers, such as EW (challenge to identify and measure efficacy and to trace the fate and behaviour of EW products in the environment) and mCDR.

The clusters are show schematically below (Figure 4-13).

Figure 4-13 Clustering of MRV-ability



5 Conclusions

The review herein highlights the extraordinary momentum that has been generated around CDR as a climate solution in a relatively short space of time. It also shows that markets are rapidly responding to the momentum by crowding in finance for CDR start-ups of many varieties and by creating demand signals through corporate procurement programmes for the CDR credits these firms intend to supply. Evidently, governments have been struggling to keep pace.

Reasons persist for being both positive and circumspect about the role of CDR in ambitious climate action: on the one hand, CDR approaches seem essential to achieving the Paris Agreement goals; on the other, CDR poses significant challenges and moral hazards for climate policymaking.

5.1 Characterising and evaluating CDR

The technical review of CDR highlights that questions remain over the foundational science and social acceptance underpinning most CDR methods. For several methods, evidence of their efficacy and efficiency, especially under a wide range of real-world conditions, remains uncertain (e.g. functionality in certain circumstances; GHG footprint of inputs in different situations). For others, durability can be problematic unless managed appropriately (e.g. soils and forests). Another group of methods face significant social acceptance and legal impediments that will likely challenge significantly scaled-up deployment (e.g. geological storage and mCDR).

In all cases, such hurdles impact upon their availability and timeliness to scale to meet climate goals over the next 25 years or so. As such, the view that a portfolio of CDR methods is likely to be needed to meet the Paris Agreement goals is reaffirmed.

5.2 Addressing 'MRV-ability' and accounting needs for CDR

The current knowledge and understanding of the efficacy of some CDR methods is hampered by observational challenges. For CDR methods such as SOC, EW and mCDR among others, challenges persist for monitoring CO_2 flux rates, C stocks (and therefore discernible C stock changes over time) and the fate and behaviour of C carriers in the environment (e.g. bicarbonate). Despite stoichiometric models indicating that several CDR methods can be expected to deliver a CO_2 drawdown effect, monitoring of field trials have in many cases been unable to corroborate these hypotheses.

The review of MRV for the various CDR methods indicates that recent focus has almost exclusively been tilted towards developing project-based methodologies by which to certify and credit CDR activities. Such methods are inherently consequential, relying on a baseline scenario and crediting baseline to infer a level of net CO_2 removal being achieved by a given CDR activity. These approaches usually involve a lifecycle perspective with wide boundaries.

The need for a baseline introduces significant variability due to the challenges in designing and implementing methods by which to determine a counterfactual or “what if” scenario at the level of individual project activities. Establishing counterfactuals is a notoriously difficult subject, and additionality testing applied in many crediting programmes to date has been subject to widespread post hoc criticism. So far, with the exception of the NZ ETS, little attention has been given to the possibilities for attributional approaches to CDR that can avoid many of the project-based accounting challenges (i.e. application of site level quantification methodologies with narrow boundaries).

Moreover, assessment of the contributions of Parties towards the Paris Agreement’s goal will be based on the measured GHG emissions by sources and removals by sinks and reservoirs as compiled and reported in national GHG inventories (NGHGIs). This situation poses two critical issues for the current approach to CDR crediting or certification:

- **Policy utility**. If certified and/or credited CDR activities do not create a symmetrical and equivalent amount of CDR in the host country NGHGI—a problem that can be termed inventory visibility—then any policy designed to incentivise CDR projects will lack political utility for the host Party government. Environmental integrity problems will arise where such certificates or credits allow an acquiring corporate entity to make neutralisation claims against its MRV’d emissions, but such benefits are not also bestowed upon the country hosting such activities. These challenges could also be exacerbated by trans-boundary movements of products within CDR value chains, which could also compromise OMGE.
- **Long-term responsibility**. Host countries are ultimately the underwriter of last resort for carbon reversal from most enhanced C sinks and reservoirs that result from CDR activities. The country should be monitoring these reservoirs and, where a reversal occurs, counting the CO_2 fluxes against their national climate targets (i.e. their NDC). However, seemingly to date the full implications of this arrangement have not been entirely realised. Better understanding over the liability for any carbon reversals may impair countries’ willingness to host CDR activities, a problem that can be further exacerbated by inventory visibility. These risks need to be characterised and managed in order to support countries in accepting these arrangements.

Ocean-based CDR methods pose unique challenges in these regards. Since the planetary oceanic C reservoir falls outside of national MRV frameworks, any CO_2 drawdown resulting from such methods will be neither visible in any country’s NGHGI nor subject to any host country monitoring and reporting in an NGHGI that could offer means to address liability for any carbon reversal.

At the time of writing, further sensitization to these important matters, and a more nuanced dialogue around approaches to address them, appears vital.

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Annex A – CDR method fiches

A-1 Biological capture and storage

	Afforestation/reforestation (A/R) ('forestation')	Improved forest management (IFM)	Soil organic carbon (SOC)	Blue carbon (coastal wetlands)
Brief description/typology	**Afforestation** involves the planting of tress on land previously never forested. **Reforestation** relates to the planting of trees on land that was previously forested but deforested at some point in recent history (under the Kyoto Protocol this was set with a cut-off date of 31 December 1989, or at least 20 years prior to the start of the activity). Other forestry activities that may deliver carbon removals include: - Improved forest management (IFM). - Agroforestry (planting of trees on agricultural land) Converting land to forests will generally increase the size of the terrestrial C stock on a parcel of land compared to other, prior, uses (e.g. cropland, grassland, abandoned land).	Various sustainable or improved forest management (IFM) practices can increase C stocks in managed forests. Changes in harvesting practices/intensity (extended harvest rotations; retention harvesting), actions to reduce disturbances and measures to increase biomass growth (thinning, drainage, new species) can lead to increased C stocks across all carbon pools (AB, BB, DOM, SO). Such management actions are well established, but subject to variable implementation. The status of the individual forests (age structure; economic factors) strongly influences potential for forest C stocks to be increased by IFM.	Mineral soils may be managed carefully so as to increase soil organic carbon content (SOC). Management options include cover cropping, improved crop rotations (e.g. through inclusion of legumes and other nitrogen fixing crops), deep rooting crops, conversion from arable to grassland and other management of grazing land and grass-land to increase soil organic carbon (SOC) levels. (Bey et al. 2021)	Peatland and wetland restoration seeks to slow and eventually reverse the degradation of organic soils. When drained, peatlands and wetlands release stored carbon, methane and nitrous oxide (Bey et al., 2021). Rewetting or restoring drained peatlands and wetlands predominantly involves blocking drainage channels to raise the water table. This process slows the release of carbon and allows the peatland to increase its carbon stock through plant growth and deposition. Modified management of coastal wetlands (salt marshes and flood plains) to reduce drainage and increase soil organic carbon also falls within the scope of "blue carbon".
CO_2 capture pathway	**Biological capture** (natural uptake absorption by trees through photosynthesis). Accrual of soil organic carbon (through litter and DOM)	**Biological capture** (natural uptake absorption by trees through photosynthesis). Accrual of soil organic carbon (through litter and DOM)	**Biological capture** (natural uptake absorption by plants through photosynthesis). Accrual of soil organic carbon (through litter and DOM, usually through changes to cultivation techniques in croplands and grassland)	**Biological capture** (natural uptake absorption by trees through photosynthesis). Accrual of soil organic carbon (through litter and DOM)
CO_2 storage medium	**Biogenic C pool** (wood; litter/DOM; soil)		**Soil C pool** (organic C pool)	
CO_2 storage type	Semi-closed (above ground biomass)	Open	Open	Open
Technical maturity/TRL	TRL 9	TRL 7 to 9	TRL 8-9	TRL 8-9
Technical mitigation potential	0.5-10 $GtCO_2$-eq/yr (2020-2050) (Bey et al. 2021; Smith et al. 2023; SoCDR)	0.4-2.1 $GtCO_2$/yr (2020-2050) (Bey et al. 2021) 0.1-2.1 $GtCO_2$/yr (Smith et al. 2023; SoCDR)	2-5 $GtCO_2$-eq/yr (2030) (Bey et al. 2021) 0.6-9.3 (Smith et al. 2023; SoCDR)	Wetland potential (including avoided removals + restoration): 2.7 $GtCO_2$/yr (2030). Coastal wetlands restoration: 0.2-0.8 $GtCO_2$/yr (2020-50) Peatland restoration: 0.2-0.8 $GtCO_2$/yr (2020-50) (Bey et al. 2021) <1 $GtCO_2$/yr (Smith et al. 2023; SoCDR) 0.003 $MtCO_2$/yr (Powis et al. 2023)
Cost (USD/tCO_2)	0-240/tCO_2 (Smith et al. 2023; SoCDR)	n/a	<40/tCO_2 (Bey et al. 2021)	10-100/tCO_2 (Bey et al. 2021)
Actors, activities and projects	Any unforested land can be considered as a candidate for afforestation/reforestation. The types of individual project activities are difficult to characterise.	Any managed forest can be considered as a candidate for IFM. The types of individual project activities are difficult to characterise.	Any managed cropland or grassland can be considered as a candidate for SOC increase. The types of individual project activities are difficult to characterise. Some specialists in the field exist: **Indigo Ag** (U.S.) Has been pioneering methodologies for robust soil carbon crediting, including methods by which to monitor farming activities. Verra VM0042 is the key methodology (although being revised at the time of writing, February 2024). **Nori** (U.S.) **Agreena** (EU/Denmark)	Any unforested managed land (primarily cropland or grassland) can be considered as a candidate for blue carbon. The types of individual project activities are difficult to characterise.

	Afforestation/reforestation (A/R) ('forestation')	Improved forest management (IFM)	Soil organic carbon (SOC)	Blue carbon (coastal wetlands)
Proven efficacy/scalability	Converting land to forest leads to the enhancement of the terrestrial carbon sinks.	Age-class effects can significantly skew the potential for IFM at given points in time.	Durability of SOC and scope for rapid depletion following change in management (e.g. tillage/ploughing) pose significant challenges for soil organic carbon storage as a climate mitigation solution. Accurate and consistent measurement of SOC stocks (and stock change over time) poses challenges due to heterogeneity.	Similar to SOC
Factors affecting GHG effectiveness	Availability of land to be converted to forested land. Quality of land to be forested. Energy and fertiliser inputs.	Age-class effects can significantly skew the potential for IFM at given points in time. Differences in opinion remain over the sequestration efficacy of multiple shorter rotations (when younger trees grow faster) versus long rotations which allow for more consistent growth and do not suffered from forest rebound problems (e.g. the challenges to establish new trees on clear cut land).	Durability. Measurability (given heterogeneity even at local scales)	Durability. Measurability (given heterogeneity even at local scales)
Legal and environmental aspects & safeguards	Local rules and standards	Local rules and standards	Local rules and standards	Local rules and standards
Geographical, socio-political and other factors	Land competition	Land competition	Land competition	Land competition

A-2 Engineered geostorage

	Bioenergy with carbon capture and geological storage (BECCS)	Direct air capture and geological storage (DACS)	BEC / DAC with mineral storage	Bio-oil injection
Brief description/typology	High-rate continuous capture of CO_2 from concentrated point sources of biogenic emissions (biomass fired power plants; waste-to-energy plants; biomass fermentation offgas) Application of known and understood techniques involving the chemical capture of CO_2 and its subsequent transport and injection into geological reservoirs for long-term storage. Globally, the capture of fossil CO_2 emissions sources has been proven at various scales and in various settings. To date, the capture of CO_2 from biogenic sources and from waste incinerators has been piloted but is yet to be implemented at significant scale anywhere in the world.	High-rate continuous capture of CO_2 from dilute concentrations in ambient air. Application of known and understood techniques involving the chemical capture of CO_2 and its subsequent transport and injection into geological reservoirs for long-term storage. Globally, the capture of fossil CO_2 emissions sources has been proven at various scales and in various settings. To date, the capture of CO_2 directly from the air, from biogenic sources and from waste incinerators has in some cases been piloted but is yet to be implemented at significant scale anywhere in the world. To date, the capture of CO_2 directly from the air has been piloted but is yet to be implemented at significant scale anywhere in the world.	As for BECCS or DACS, but with the use of basalt as storage media. Basalt (dunite, periodite etc) contains large amounts of calcium- and magnesium-rich silicate minerals (olivine, serpentine etc), which react to form carbonates when exposed to CO_2 in solution (i.e. as carbonic acid). This is the same process as occurs in the natural silicate-carbonate weathering cycle taking place in nature (see ERW)	Production of biogenic oil from waste biomass residues, and its injection into subsurface geological reservoirs. Bio-oil or bio crude is derived from the pyrolysis of biogenic materials in the range 350-600°C. Methodology from Isometric includes salt cavern storage (although no proposals for such could be found).
CO_2 capture pathway	**Biological capture** (natural uptake absorption by trees through photosynthesis). **Chemical capture using solid or liquid sorbents.** In the case of biomass, the capture of CO_2 takes place during growth of biomass. The retention of biogenic CO_2 in the geological carbon pool constitutes its sequestration away from the atmosphere.	**Chemical capture using solid or liquid sorbents.** Two main systems: solid sorbent process and potassium carbonate cycling.	As for BECCS & DACCS	**Biological** (plant uptake of atmospheric CO_2) The capture of CO_2 takes place during biomass growth. The harvesting of the biomass and its conversion to oil and ongoing retention as biogenic C within the geological C pool constitutes its sequestration away from the atmosphere.
CO_2 storage medium	**Geological C pool** Geological reservoirs (e.g. saline formations)		**Geological C pool** Alkaline (mafic/ultramafic) geological rock formations (e.g. basalt or peridotite)	**Geological C pool** Geological reservoirs (e.g. saline formations). Salt caverns also considered (see Isometric methodology).
CO_2 storage type	Closed	Open	Depends	Closed
Technical maturity/TRL	TRL 5-6	TRL 6	TRL 4	
Technical mitigation potential	0.5-11 $GtCO_2$/yr. (IPCC 2019; SoCDR, Smith et al., 2023)	5-40 $GtCO_2$/yr (IPCC 2019; SoCDR, Smith et al., 2023)	n/a	n/a
Cost (USD/tCO_2)	15-400/tCO_2 (IPCC 2022; Smith et al. 2023; SoCDR)	100-300/tCO_2 (IPCC 2022; SoCDR, Smith et al., 2023)	n/a	473/tCO_2 (based on Frontier deal below)
Actors, activities and projects	IEA CCS Database (July 2023) lists 3 operational BECCS plants in the world (excluding other forms of BiCRS - see "Other"). Operational: - Archer-Daniels-Midland (ADM), Decatur, U.S. (0.5 $MtCO_2$/yr) - Conestoga (Arkalon/Bonanza projects; 0.3 $MtCO_2$/yr) - Red Trail Energy (0.18 $MtCO_2$/yr). Under consideration: - Drax (although not included in UK CCS Track I or II) - Stockholm Exergi biomass (district heating) - Fortum Oslo Varme (waste-to-energy) - Enfinium (waste-to-energy))	No DAC plant is presently coupled to deep geological storage. A number of actors involved in developing concepts across a range of storage media. Developers/operators - Carbon Engineering (CE; Canada) - Climeworks (various projects in Switzerland and Iceland, incl. mineralization) - 1PointFive (SPV of Occidental for DAC; U.S.; various projects worldwide) - Heirloom (U.S., start-up using limestone to capture CO_2) - Global Thermostat (U.S. start-up exploring 0.1 $MtCO_2$/y plant in Colorado) - Air Capture LLC (U.S.) - Removr (U.S.) - CarbonCapture Inc. - Ucaneo (Germany) - Sustaera (U.S.)	One DAC plant is currently coupled to geological storage with mineralisation (the project is also associated with acid gas injection from a geothermal power plant). Operational: - Climeworks/Carbfix, Iceland (Orca project, 0.004 $MtCO_2$/yr) Under consideration/construction: - Mammoth (Climeworks/Carbofix, 0.036 $MtCO_2$/yr) - Air Capture (U.S) - 44.01 (Oman)	**Charm Industrial** Uses pyrolysis to heat biomass (e.g. agricultural residues such as corn stover or forestry trimmings) to release biogenic oil-like substance. Sites presently in Kansas and Fort Lupton (CO) Has received significant investment and signed various offtake agreements (e.g. Frontier = $53m for 112 $ktCO_2$ rem; JP Morgan = 28,500 (No Suggestions) over 5 years; Zopeful = ???)

	Bioenergy with carbon capture and geological storage (BECCS)	Direct air capture and geological storage (DACS)	BEC / DAC with mineral storage	Bio-oil injection
Proven efficacy/scalability	**ADM Illinois Basin - Decatur Project** IBDP in Decatur, U.S., is the largest operational BECCS plant in the world (also called the Illinois Industrial Carbon Capture Project). The IBDP involves the capture and saline aquifer storage of up tp 1 $MtCO_2$/yr of corn ethanol fermentation offgas. The last reported injection total for 2021 was 0.444 $MtCO_2$ (US EPA, GHGRP Reporting tool). DOE sponsorship ended in 2021, having injected a total of 1 $MtCO_2$ over the period 2011-2014. The DOE sponsored an intensive subsurface monitoring research programme. **Stockholm Exergi** The municipal power company of the City of Stockholm - is proposing to capture and store 0.7-0.8 $MtCO_2$/yr from its Värtan bio-cogen district heating plant. The project has received €180 million from the EU Innovation Fund to support the project. The CO_2 will be shipped to offshore Norway (probably Northern Lights) **Drax** The largest grid connected power plant in the UK - plans to capture and geologically store biogenic CO_2. The primary project involves the ongoing switch from coal to power a the Drax power plant, its capture, transport and storage offshore in the southern North Sea. Drax estimates that it will be capturing and storing around 14 $MtCO_2$ by 2030 (the entire throughput of the Drax plan in Yorkshire). **Oslo Vaerme WTE** Had provisionally secured NOK 3 billion on the basis of securing additional finance. However, the project was not [yet] selected by the EU Innovation Fund. **Enfineum** UK-based waste management firm has considered the feasibility of several waste-CCS projects (in the UK). "The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor." (IPCC 2022) "For most of the regions, our results indicate storage capacity is not a limiting factor for CCS deployment through the rest of this century even if stringent emissions reductions are required." Kearns, J. et al., (2017). Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide. *Energy Procedia*, 114, 4697–4709, doi: 10.1016/j.egypro.2017.03.1603.	According to the IEA (2023), 27 DAC plants have been commissioned in Europe, North America, Japan and the Middle East to date. All of these plants are small-scale, with only a few commercial agreements in place to sell or store the captured CO_2, while the remaining plants are operated for testing and demonstration purposes. Climeworks (Switzerland) Operates several small-scale DACS projects, with has one operational CO_2 mineral storage project, and another under construction (see mineralisation) In 2024, the Mammoth DACS plant in Iceland was commissioned, with a rated capacity of 36,000 tCO_2/yr. Climeworks other Icelandic DACS plant (Orca) is capturing around 4,000 tCO_2/yr. 1pointFive Broke ground on a 500 $ktCO_2$ DACS facility in Texas, U.S. (Ectro Co.) in April, 2023. The JV is also planning a further 4 plants in TX, and is exploring opportunities worldwide. CE (with Oxy Low Carbon Ventures) is exploring DAC at Kollnes, Norway. Other DAC firms are at earlier stages of deployment (see also mineralisation). - Global Thermostat has proposed a 0.1 $MtCO_2$/yr DAC plant in Colorado, U.S. - Air Capture is the preferred technology provided for 44.01 (mineralisation) - Removr has ambition to launch 1 $MtCO_2$/yr plant by 2029. Part of U.S. DOE Ankeron DAC Hub (with RMI and Sustaera) - Sustaera (U.S.) plans to remove 500 $MtCO_2$ by 2040. - AirZyme (Sweden) that takes "a biomimetic approach to Climate Change" - Ucaneao (Germany) that is developing the "world's first cell-free DAC technology reversing climate change with synthetic biology" - CarbonMiner (Ukraine) packaged DAC solution - Mission Zero Technologies (UK) offers packaged DAC concept - Carbyon (Neth.) develops DAC technology - CarbonCapture (U.S.) Project Bison in Wyoming proposes to capture and store 5 $MtCO_2$/yr - Carbon Atlantis (Germany) "patented" liquid sorbent looping system. "The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor." (IPCC 2022)	**Climeworks** (with **Carbofix)** Owns and operates the largest operation DACS projecting the world (Orca) in Iceland. - Orca captures c. 4$ktCO_2$/year, which is coinjected with H_2S containing geothermal brines for storage through mineralisation reactions in mafic rock (basalt) at fairly shallow depths (up to 300 metres). - Mammoth broke ground in June 2023 (also Iceland), which plans to capture up to 36 $ktCO_2$/year. **44.01** (with **Air Capture LLC**) Planning a 0.005 $MtCO_2$/yr DAC project with mineral storage in Oman. - May 2023 - Agreed Concession with Oman's Ministry of Energy and Minerals (MEM) for commercial-scale peridotite mineralisation project - Sep 2023 - Signed cooperation agreement to use Air Capture LLC to source CO_2. **Heirloom** (U.S.) Plans to utilise limestone to remove 1 Bn tC02 by 2035. Part of U.S. DOE hub award for Project Cyprus (Louisiana), alongside Battelle and Climeworks. **Octavia Carbon** (Kenya) Promoting a DAC with mineralisation storage concept in Kenya. **Neustark** (Switzerland) Capturing biogenic CO_2 and storing it through processing with recycled concrete aggregate. **Paebbl** (Neth) Using DAC to convert captured CO_2 to mineral filler product.	Charm reports removing >7,000 tCO_2e to date. Some have argued that Charm does not remove C, but rather avoids CO_2 emissions from the burning/decay or biomass/crop residues [**the same concerns and principle applies to all types of biogenic CO_2 capture**].

	Bioenergy with carbon capture and geological storage (BECCS)	Direct air capture and geological storage (DACS)	BEC / DAC with mineral storage	Bio-oil injection
Factors affecting GHG effectiveness	**Biomass sources and zero-rating** Critical that projects utilise biomass sources where growth is balanced by harvesting to support zero-rating assumption. **Biomass source and ecology** Vital that biomass is sourced from well-managed, biodiverse (not monoculture), ecological systems which do not place excessive pressure on natural resources (e.g. water) (i.e. sustainable biomass) **Energy consumption** Stockholm Exergi claim the hot potassium carbonate (HPC) capture system they are planning to utilise will reduce the typical energy penalty of 15-29% to as low as 2% (source: EU Innovation Award fiche, dated April 2022) **Non-permanence/Reversal** Geological storage is durable (likely to store 99% of injected CO2 over 1000 years); mineral storage is less proven.	**Energy consumption** 1,200 KWh per tCO2 **Energy source** The large energy demand of DAC means that its vital that projects utilise renewable energy sources (heat and power) **Materials** Embodied carbon in chemicals sorbents can be high. Unclear on comparison with CCS. Water consumption is reportedly high for some slurry-based capture processes XXX	As for BECCS or DACS. **Energy consumption** Injectivity challenges may call for significant recycle and pressure to stimulate target storage zones (micro frac). Climeworks/CarbFix reportedly injecting CO2 dissolved in water at 200m depth. The recycle rates can be expected to be high. The extend of losses from the recycle loop remain uncertain. **Non-permanence/Reversal** Mineral storage is not as well proven as deep aquifer storage. Target zones may be tectonically active (e.g. Iceland). In the case of Neustark, the aggregate is presented as a CCU-product with permanent storage. The Gold Standard methodology developed and applied by Neustark considers "the application of CaCO3 as filler material for the construction sector as permanent storage of CO2".	**Feedstock**: availability and sustainability of agricultural residue feedstocks. **Energy use/GHG emissions from materials acquisition and injection**: the amount of energy used to acquire feedstock materials, to transport bio oil and for injection. **Diversion of biomass from other users:** potential to take biomass from other users, leading to iLUC effects. **Non-permanence/reversal:** oxidation of C in stored in reservoirs, and its subsequent emission to the atmosphere from the geological C pool.
Legal and environmental aspects & safeguards	**Above ground** No specific impediments beyond typical environmental permitting requirements for industrial activities. Need to ensure effective safeguards within any certification programme to avoid leakage risks (e.g. use of non-sustainable biomass). **Below ground** Legal and regulatory permitting requirements for geological CO2 storage a mainly limited to OECD countries, posing a potential constraint on non-OECD deployment. Precedents from Kyoto Protocol/CDM suggest that national law and the permitting of storage can be an vital pre-requisite for creditable climate mitigation activities involving geosequestration. **Other** BECCS is covered by IPCC National GHG Inventory Guidelines.	**Above ground** No specific impediments beyond typical environmental permitting requirements for industrial activities (water use, waste, emissions to air). Need to ensure effective safeguards within any certification programme to avoid leakage risks (e.g. use of carbon intensive fossil energy to power DAC plants). **Below ground** Legal and regulatory permitting requirements for geological CO2 storage a mainly limited to OECD countries, posing a potential constraint on non-OECD deployment. Precedents from Kyoto Protocol/CDM suggest that national law and the permitting of storage can be an vital pre-requisite for creditable climate mitigation activities involving geosequestration. **Other** DAC not yet covered by IPCC National GHG Inventory Guidelines. This should not be a significant barrier to deployment (Norway reported non-emitted CO2 at Sleipner since 1999, some 7 years before IPCC CCS Guidance was established)	No dedicated technical, permitting and regulatory standards for mineral CO2 storage. However, in principle, the technique could follow similar standards as applied to deep geological aquifer storage. Reportedly, the Icelandic environmental regulator has issued a CCS Permit to CarbFix aligned to the EU CCS Directive requirements (CarbFix, pers comm.)	**Direct impacts**: Unknown. **Carbon Direct & EcoEngineers** methodology "Bio-oil Sequestration Prototype Protocol for Measurement, Reporting, & Verification" requires EPA UIC Class I, II or V permitting (notably, not Class VI) **Isometric** draft methodology for "Bio-oil Geological Storage" also requires: - For "Bio oil storage in Permeable Reservoirs": EPA UIC Class I or V (notably, not Class VI) - For "Biomass or Bio oil Storage in Salt Caverns": EPA UIC Class V (notably, not Class VI) **Indirect impacts**: similar to biochar.

	Bioenergy with carbon capture and geological storage (BECCS)	Direct air capture and geological storage (DACS)	BEC / DAC with mineral storage	Bio-oil injection
Geographical, socio-political and other factors	The efficacy of widespread BECCS use is subject to considerable contention among researchers and policymakers. While IAMs seem to overwhelming rely on BECCS to achieve net zero, the land impacts of these estimates are often poorly reported. For instance, analysis suggest a land area in the region 100-800 million hectares would be needed to achieve, BECCS deployment estimates under IPCC SR1.5 scenarios P1 and P4 respectively (Fajardy et al., 2019, Imperial College). The territory of India equals around 330 million hectares. On the socio-political front, the competition for land for bioenergy cultivation and other uses remains a persistent challenge. On the environmental front, concerns persist over the conversion of high C stock land to bioenergy crop cultivation (e.g. mangrove swamps), with the resultant emission of the stored C. Furthermore, the climate impact of such conversions are poorly recorded in many parts of the world, due to the challenges of LULUCF monitoring and inventory compilation. Some (e.g. Brack and King, 2020) argue that, among others, the IAM results used in SR1.5 ignore the counterfactual of using land producing biomass feedstocks to otherwise grow mature forest. Concerns also persist about the biodiversity impacts of that could result in the conversion of existing forest land into monoculture plantations.	Flexibility of DAC offers the potential to site capture equipment in close proximity to storage sites. However, the utility of the above is constrained by the co-existence of low- or zero-emissions energy supplies (in order to maintain a negative carbon balance).	In situ mineralisation restricted to areas with near-surface or outcrops of mafic and ultramafic rocks. The potential for mineral storage in "construction products" is potentially widespread, although the rate/demand for utilisation could be a limiting factor.	Similar to other types of geological storage in respect of e.g. leaks, subsurface migration, and contamination of other subsurface resources. In the U.S., the draft crediting methodology from Carbon Direct suggests wells are covered by Underground Injection Control Class II well rules.

A-3 Engineered biostorage

	Enhanced rock weathering (ERW) on croplands	Biochar (BC)	Biomass burial (terrestrial)	Biomass use
Brief description/typology	Chemical weathering is the natural breakdown of minerals in rocks through chemical transformation. Weathering by hydrolysis and carbonation involves CO2 dissolved in rainwater acting as a weak carbonic acid to break down silicate minerals in rocks (the silicate - carbonate geochemical cycle). Carbonate rocks (e.g. limestone) are also weathered by hydrolysis and carbonation reactions. Mafic and ultramafic (basaltic) rocks (e.g. gabbro, dunite, peridotite, websterite) contain large amounts of silicate bearing minerals (e.g., olivine [Mg2SiO4], serpentine [Mg3Si2O5(OH)4]), which are naturally weathered through hydrolysis-carbonation (acid-base) reactions. Calcite rocks (metamorphosized limestones) are a source of wollastonite [CaSiO3], which also absorbs CO2 in weathering to calcium carbonate (CaCO3) and silica (SiO2). ERW involves the amending of soil with acquired and crushed calcium- and magnesium-rich silicate rocks (per above) to accelerate CO2 sequestration. Hydrolysis and carbonation reactions liberates base cations, which leads to conversion of atmospheric CO2 to dissolved inorganic carbonate (primarily bicarbonate; HCO3-), which leaves fields in drainage water, and may ultimately end up in the ocean. CO2-derived dissolved inorganic carbon may also be sequestered through formation of soil carbonate minerals (with lower sequestration rates). The chemical pathways are envisaged: Pathway 1 for calcium ions:			

	Enhanced rock weathering (ERW) on croplands	Biochar (BC)	Biomass burial (terrestrial)	Biomass use
Technical maturity/TRL	TRL 3-4	TRL 6-9		
Technical mitigation potential	2-4 GtCO2/yr (IPCC 2023) 3-4 GtCO2/yr (SoCDR, Smith et al, 2023) 0.5-2 GtCO2/yr (Beerling et al., 2020)	0.3-6.6 GtCO2/yr (IPCC 2019; SoCDR, Smith et al, 2023)	No data.	
Cost (USD/tCO2)	50-200 (IPCC 2023; SoCDR, Smith et al, 2023)	10-345 (IPCC 2019; SoCDR, Smith et al, 2023) 9-120 (Bey et al. 2021)		
Actors, activities and projects	**Number of start-ups moving forward with ambitious ERW plans. Below is a selection.** **Cascade Climate** (U.S.) Focus on ERW market development, underpinned by its scientific evidence base. Recently reported a new initiative to develop a community ERW quantification standard (https://cascadeclimate.org/introducing-the-cqs) **Lithos Carbon** (U.S.) SF based start-up. Dec '23, signed an offtake agreement with Frontier for $57.1m for 154,240 tons of CO_2 between 2024 and 2028 ($370/tCO2e) **Un-Do** (UK) Scottish start up with "..ambition – to be the first company to remove 1 million tonnes of CO2 with the aim of removing a billion, once and for all". Advocates using wollastonite dust as an alternative or in addition to lime spreading to help manage soil pH. Has agreements with McLaren, British Airways, Standard Chartered and CUR8/Rethinking Removals. Has spread 5,500 t Wollastonite on 1000 ha in Ontario, with aim of 2 ktCO2 captured in 2 years. Investment also by Zopeful. **Reverce** (Germany) Developing ERW offering, working with Carbon Drawdown. **Carbon Drawdown Initiative** (Germany) Running two ERW pilots in Germany and Greece ("Project Carbdown"). Spreading various basalts (e.g. dunite) and biochar on 90m x 3 m plots @ 4 kg/m2 (40t/ha) rock + 0.2 kg/m2 biochar. **Eion Carbon** (U.S.) In 2023 delivered 50tCO2e removal credits to Stripe. **- InPlanet** (Brazil) - **Silica** (Mexico)	Wide range of actors already active or moving into this space. Below is a selection. **- Wakefield biochar (U.S.) -** so far issued the most credits in the VCM **(~35,000 tCO2)** **- Pacific Biochar (U.S.) - so far delivered -26,000 tCO2 to VCM** - **CarboCulture** (U.S., UK, Finland) - "Building a rapidly scalable biochar carbon removal solution", with first pilot located near Helsinki, FI. Has raised >EUR 6 million in angel investment and research grants (incl. DE Govt). Carbon credit offtake agreements with Zendesk and Rothschild & Co. - **Circonomy** (Singapore) - **Circular Carbon** (Germany). "Producing biochar from organic residues, creating innovative solutions to restore the lost natural balance in agricultural soils." - **NovoCarbon** (Germany). Developed 3 x sites across Germany. Registered under Puro.Earth std. - **Exomad Green** (Bolivia). Forest products co., with 32,000 tCO2 offtake between Carbonfuture and Microsoft) - so far delivered ~24,000 tCO2 to VCM - **MashMakes** (Denmark/India). Planning 2 x 30,000 tCO2/yr biochar plants . Investments by Zopeful. - **Oregon Bicohar Solution**s (U.S.) - **Carbon Cycle 001** (Germany) - **Sonnenerde Pyreg** (Austria) - **ECHO2 Holla-Fresh** (Australia) A list of Puro.Earth registered suppliers can be found here: https://carbon.puro.earth/CORC-co2-removal-certificate/supplier-listings	**Carbonlockdown Project** is an initiative of Uni. of Maryland focussed on biomass burial. Lists two main projects **1. Potomac Project** (Maryland, U.S.) Aim to bury 5000 tCO2-e of coarse woody biomass in a wood vault in Chesapeake Bay. Wood sourced from forest residues. **2. Montreal Project** (Montreal, Canada) 35 tonnes of wood buried in a trench was still intact 9 years later. Claimed to show the durability of storage. **InterEarth** (Australia) Proposing to coppice purpose-grown trees and bury the harvested biomass in salt pans to preserve the biomass. **Reverse Carbon Mining** (Austria) Proposing to store biochar in open put or shaft mines.	Some recent start-ups include: **Nellie Technologies** Use biomass to manufacture biochar and bioaggregates. **Neustark** (Switzerland) Using biogenic CO2 to treat crushed waste concrete, which is then used as an aggregate. Carbon8 (U.K.)

	Enhanced rock weathering (ERW) on croplands	Biochar (BC)	Biomass burial (terrestrial)	Biomass use
Proven efficacy/scalability	While theoretically feasible, the true efficacy of ERW is unproven. Two main methods employed to measure efficacy to date: 1. Modelling estimates 2. Laboratory/mesocosm experiments. In the case of the latter (2) "experiments on organic-rich acidic soils incubated with olivine revealed that gross removal of CO_2 assessed from the increase in Mg^{2+} concentrations on soil exchangeable sites was between rate), no net increase in CO_2 removal was observed due to increased rates of soil respiration" [from: Larkin, C et al., 2022. Frontiers in Climate. https://doi.org/10.3389/fclim.2022.959229] Field-scale experimentation is limited, but a few trials are underway in U.K., Germany, Greece and Malaysia. However, measuring and tracing the fate and behaviour of applied rock particles and the products of weathering is difficult to measure in field, and the efficacy of storage is difficult to monitor due to the open nature of the containment media. Application of olivine to ryegrass in a pot experiment was observed to increase gross CO_2 uptake by ~0.5–4.4 tCO_2 ha^{-1} yr^{-1} (Berge et al., 2012), although amendment of agricultural soils (with and without crops) with olivine-bearing dunite showed significantly lower rates of CO_2 removal (0.02–0.05 tCO_2 ha^{-1} yr^{-1}; Amann et al., 2020) [Larkin et al., 2022]. Early results from the Malaysia field trials indicated that for " ... all three plots together, the average (±1SD) amount of CO_2 removal was 3.8 ± 0.8 untreated catchments over the continuous monitoring period (Figure 10). Thus, application of silicate rock did not result in a change in CO_2 removal via alkalinity generation outside of the error range. The quantity of CO_2 removed over the continuous monitoring period was similar for both the treated and untreated catchments in plots 1 and 2..." [Larkin, C et al., 2022.	Theoretically, the transfer of C from short-cycle rotation in the biological-atmospheric cycle to the slower-cycle involved soil C accumulation can lead to the removal and sequestration of atmospheric CO_2. The durability of biochar remains subject to some debate. IPCC (2019) proposes 100-year default factors for inorganic C retention in soil from biochar application. Similarly, the effects of adding inorganic C to the soil remain uncertain, including in respect of the breakdown of organic C present in receiving soils (soil priming). Experimental results remain mixed in these respects. Durability of soil inorganic carbon (SIC) is poorly researched, and some indications are that breakdown accelerating due to soil acidification due to elevated atm CO_2 concentrations (Ferdush and Varun 2021, https://doi.org/10.1016/j.catena.2021.105434)	As for other biogenic capture methods. **Efficiency**: comparability of carbon removal efficiency relative to other uses of biomass (with CDR, e.g. BECCS; Biochar; bio-oil injection) **Non-permanence/reversal risk**: Long-term durability and risk of non-permanence of storage remains untested and difficult to discern. The form of chemical bond (e.g. mineralised carbon) is increasingly considered as a key determinant of durability/reversal risk.	

	Enhanced rock weathering (ERW) on croplands	Biochar (BC)	Biomass burial (terrestrial)	Biomass use
Factors affecting GHG effectiveness	**Mineral content of source rock**: the level of reactive minerals present in the source rock applied to fields. **Mineral reactivity** (CO_2 uptake rates): reaction rates of deposited material. **Particle size** (crushing/grinding): effect of particle size on weathering rates, and the energy trade offs involved. **Energy use/GHG emissions**: level of energy needed to acquire (extract, transport, crushing, commutation, transport) and apply materials to croplands. **Ambient conditions**: temperature, humidity and soil pH affect weathering rate. **Impact of in situ byproducts**: effect of clay formation on mineral weathering. **Depositional environment**: the ultimate residing place for bicarbonate and carbonate weathering products **Non-permanence and reversal**: bicarbonate conversion to carbonate leads to 1 mole CO_2 emitted (e.g. in the case of carbonate formation or synthesis by marine organisms)	**Feedstock**: the nature of carbonaceous feedstock will affect the extent of removals. Pyrolysis of plastics, tires or other fossil C derived feedstocks do not result in carbon removal (but may be emission reductions). **Energy use/GHG emissions from materials acquisition and application**: the amount of energy used to acquire feedstock materials, and to spread biochar. **Diversion of biomass from other users**: potential to take biomass from other users, leading to iLUC effects. **Priming (negative)**: breakdown of organic C in soil by microbes, which can increase as a result from biochar addition. **Additionality: the extent to which conversion of biomass to biochar diverts and replaces/substitutes addition of organic C materials to soil (e.g. conversion of biosolids to biochar)** **Non-permanence/reversal**: oxidation of C in stored biochar, and its subsequent emission to the atmosphere from the soil C pool. In these regards, IPCC 2019 proposes the following "permanence factors" for the fraction of biochar derived from different production methods remaining in soil after 100 years: 1. High temperature pyrolysis and gasification (> 600 °C) 0.89 ± 13% 2. Medium temperature pyrolysis (450-600 °C) 0.80 ± 11% 3. Low (350-450 °C) 0.65 ± 15% Statement on biochar: "...supply-chain emissions, biomass feedstock source, land use change, effects of biochar on greenhouse gas emissions from soil, biochar effects on plant productivity, and baseline situation are important for a full assessment of biochar as a climate change mitigation option." https://biochar.systems/durability-statement/	As for other types of biogenic C storage in soil and/or biochar production.	

	Enhanced rock weathering (ERW) on croplands	Biochar (BC)	Biomass burial (terrestrial)	Biomass use
Legal and environmental aspects & safeguards	**Direct impacts**: Four major groups of ERW products: (II) Silicic acid ($Si(OH)_4$) "silicate" (III) Certain alkaline earth metals like calcium (Ca^{2+}) and magnesium (Mg^{2+}) but potentially also alkali metals like sodium (Na^+) and potassium (K^+) (IV) a variety of "trace metals" associated with the minerals. Among these, iron (Fe^{2+}, or oxidized aqueous species) and nickel (Ni^{2+}) are of concern. These elements occur in high concentrations in basic and ultrabasic rocks (e.g., dunite), which are the most widely recognized source rocks for EW/OAE (Schuiling and Krijgsman, 2006; Hartmann et al., 2013). However, depending on the mineral selected, a wider variety of trace constituents should be considered in the future (from: Bach et al., 2019, Front. Clim. 11 Oct 2019; https://doi.org/10.3389/fclim.2019.00007) **Puro.Earth (ERW brochure/draft methodology)** indicates that it [will] require registered projects to take account of: - Rock toxicity levels (e.g. Ca, Mg) - Rock sourcing (must be done in line with local regulations) - Application site (environmental risk assessment & food safety must be carried out. Right or authorisation to spread must be provided) - Local communities (evidence of informed consent, including acceptable contaminant levels and environmental risks, plus ongoing engagement) - Occupational hazards (measures take to mitigate H&S risks) - Surrounding ecosystems (low risk of -ve impact, incl soil, biodiversity, water, air. Crop quality & yield reports) Compliance with marine pollution protection law: - Deposition of bicarbonate into marine environment from land-based sources may be within purview of UNCLOS Article 194, 207 and 213 (take measures to reduce and control any source of marine pollution, including land-based source) - Regional seas policies and frameworks may also impact upon eligibility. For example OSPAR convention covers land-based sources of pollution in the North East Atlantic, and others apply to other regions (e.g. Kuwait Protocol, South East Pacific Protocol, Mediterranean Protocol etc.)	**Soil C pool** Addition of inorganic C to soil. According to the International Biochar Initiative (2010) "At this time, insufficient field data is available to make general recommendations on biochar application rates according to soil types and crops". They also note the dependence on the biochar type. Several studies have reported positive effects of biochar application on crop yields with rates of 5-50 tonnes of biochar per hectare, with appropriate nutrient management. The International Biochar Initiative (2010) also notes that biochar can provide beneficial effects over several growing seasons in the field, and therefore does not need to be applied with each crop, as is usually the case for manures, compost, and synthetic fertilizers. Further analysis required to address the possible maximums of inorganic biochar C application to soil.	Unknown	Interactions with HWP accounting methodologies.
Geographical, socio-political and other factors	Fate and behaviour of weathering products unknown, and may cross boundaries or enter international waters. No clear way for GHG removals to be recorded by countries. Fit with soil liming CO2 emissions protocol may require further consideration.	Dedicated plantations for biochar production prone to same risks as other forms of managed forestry.	Unknown	

A-4 Ocean storage (marine CDR)

	Coastal Enhanced Weathering (CEW)	Ocean alkalinity enhancement/alkalinisation (OAE)	Ocean fertilisation / Artificial upwelling (AU) / Ocean storage of biomass (OSB)	Electrochemical oceanic carbon removal and storage
Brief description/typology	Similar to ERW and OAE, except in coastal zones. Chemical weathering is the natural breakdown of minerals in rocks through chemical transformation. Weathering by hydrolysis and carbonation involves CO2 dissolved in rainwater acting as a weak carbonic acid to break down silicate minerals in rocks (the silicate - carbonate geochemical cycle). Carbonate rocks (e.g. limestone) are also weathered by hydrolysis and carbonation reactions. Mafic and ultramafic (basaltic) rocks (e.g. gabbro, dunite, peridotite, websterite) contain large amounts of silicate bearing minerals (e.g., olivine [Mg2SiO4], serpentine [Mg3Si2O5(OH)4]), which are naturally weathered through hydrolysis-carbonation (acid-base) reactions. Calcite rocks (metamorphosized limestones) are a source of wollastonite [CaSiO3], which also absorbs CO2 in weathering to calcium carbonate (CaCO3) and silica (SiO_2). CEW involves **modifying partial pressure of CO_2 in seawater** by changing pH through alkalinisation (i.e. charge balancing of base cations produced by weathering by the formation of bicarbonate (HCO3-) ions). The first step is the conversion of dissolved CO_2 in the water column to bicarbonate and carbonate. The second step is air-sea gas exchange that removes CO2 from the atmosphere into seawater to restore equilibrium partial pressure. Method entails spreading crushed and commutated calcium- and magnesium-rich silicate rock onto coastlines where it can dissolve in seawater (Bach et al. 2019). Relative to ERW, it is surmised that the natural wave and tidal forces in CEW catalyse the weathering rate, relative to spreading alkaline minerals on land.	Similar to ERW and CEW, except involves direct deposition of calcium- and magnesium-rich silicate crushed rock into seawater. OAE involves **modifying partial pressure of CO_2 in seawater** by changing pH through alkalinisation, with the resultant air-sea gas exchange removing CO_2 from the atmosphere into seawater to restore equilibrium partial pressure. Increasing the alkalinity (and pH) of seawater results in the conversion of dissolved CO_2 to bicarbonate and carbonate, with a resultant decrease in the partial pressure of CO_2 in seawater. When applied at the ocean surface it can promote either the uptake of CO_2 from, or the reduce the release (outgassing) of CO_2 to, the atmosphere (depending on the initial air-sea CO2 gradient). Both cases lead to a net reduction in atmospheric CO_2 by increasing the oceanic pool of dissolved inorganic carbon. Various pathways under consideration through which to anthropogenically enhance seawater alkalinity (i.e. to increase proton acceptors in seawater), but mostly the approach involves spreading ground up rock.	Removal of dissolved C in seawater (bicarbonate) and fixing it in biomass through the enhanced cultivation of marine macroalgae (primary production) or sinking of other (terrestrial) sources of biomass. Dissolved C removed from the water column is replaced by removal of CO2 from the air by air-sea gas exchange. **Ocean fertilisation**: Since marine productivity is usually limited by minerals such as iron and fertilisers (e.g. phosphorous and nitrogen), the anthropogenic introduction of these minerals is often considered (e.g. iron filings). The removal of bicarbonate by marine organisms in principle leads to further removal of CO2 from the atmosphere through air-sea gas exchange. **Artificial upwelling**: a form of ocean fertilisation, drawing minerals up from the deep ocean. Pump deep oceanic water to surface using e.g. pipes. Can induce mCDR by seawater in several ways: 1. Increasing nutrient concentration (increasing marine primary production and thereby removing bicarbonate from seawater) 2. Reducing surface temperature (with resultant effects on CO2 partial pressure and air-sea gas exchange) **Ocean storage of biomass**: similar in principle, but not always involving fertilisation. Rather, OSB tends to involve using structures to cultivate marine macroalgae, which are subsequently sunk to the ocean floor. Some concepts may also involve the use of terrestrial biomass (Rewind) or a combination of terrestrial biomass sinking enhanced by marine algae cultivation (Running Tide).	Involves **modifying partial pressure of CO2 in seawater** by physically removing dissolved C (bicarbonate/carbonate ions) from it using electrochemical techniques in dedicated C capture plant. . The resultant air-sea gas exchange removes CO2 from the atmosphere into seawater to restore equilibrium partial pressure. The CO2 removed from seawater must also be captured and durably stored (e.g. geologically) [rather than emitted to the atmosphere] for the process to deliver net climate benefits.
CO2 capture pathway	**Geochemical** (air-sea gas exchange) Process utilises the natural CO_2 equilibration that will result from changes in seawater pH and CO_2 partial pressure between atmosphere and sea water. Alkaline material (e.g. crushed and ground mafic rocks such as olivine or alkaline waste such as fly ash) is spread in coastal environments ('beach nourishment'), where wave and tide action bring the materials into contact with seawater. The dissolution of the olivine in seawater over time leads to pH reduction. The reduced pH changes the partial pressure of CO2 in seawater, with air-sea gas exchanges leading to CO2 uptake by the treated seawater. Needs alkaline materials (e.g. basaltic rock) to be sourced, processed and spread in appropriate locations.	**Geochemical** (air-sea gas exchange) Process utilises the natural CO_2 equilibration that will result from changes in seawater pH and CO_2 partial pressure between atmosphere and sea water. Two basic pathways to enhance alkalinity of sea water: 1. Add alkaline materials 2. Remove acid (using electrochemistry) Alkaline material (e.g. crushed and ground mafic rocks or alkaline waste such as fly ash) must be sourced and physically added to seawater.	**Biological** Growth of algae removes dissolved C (bicarbonate) from water column, and fixes it as biomass. Removal of bicarbonate from water column will lead to C removal from atmosphere through air-sea gas exchange.	**Electrochemical** (physical removal of C ions) **+ Geochemical** (air-sea gas exchange) Apply a voltage across a stack of membranes to acidify a feed stream by water splitting. This converts bicarbonates in the water to molecules of CO_2, which can then be removed under vacuum. Alternative methods are also being proposed that avoid the need for the costly and energy intensive membranes (e.g. Kim et al., 2023. Energy & Environmental Science, https://doi.org/10.1039/D2EE03804H)

	Coastal Enhanced Weathering (CEW)	Ocean alkalinity enhancement/alkalinisation (OAE)	Ocean fertilisation / Artificial upwelling (AU) / Ocean storage of biomass (OSB)	Electrochemical oceanic carbon removal and storage
CO2 storage medium	**Oceanic C pool** (water column; primarily as bicarbonate/carbonate) and oceanic sediments Firstly, as dissolved bicarbonate (HCO-3) and carbonate ions (CO2-3). and ultimately as sediment (through biological synthesis, death and deposition).	**Oceanic C pool** (water column; primarily as bicarbonate/carbonate) and oceanic sediments Firstly, as dissolved bicarbonate (HCO-3) and carbonate ions (CO2-3). and ultimately as sediment (through biological synthesis, death and deposition).	**Oceanic C pool** (water column; primarily as biomass) and oceanic sediments + geological storage Sinking of biogenic material leads, in principle, to removal of C from fast C-cycle and storage in slow C-cycle (ocean sediments, and ultimately, geological C pool)	**Oceanic C pool** (water column; primarily as bicarbonate/carbonate) and oceanic sediments + geological storage Firstly, as dissolved bicarbonate (HCO-3) and carbonate ions (CO2-3). and ultimately as sediment (through biological synthesis, death and deposition). Removal of bicarbonate from seawater produces CO2, which must be geologically stored.
CO2 storage type	Open			Open and closed
Technical maturity/TRL	TRL 4	TRL 3-5 (oceanvisions.org)	TRL <2	TRL <3
Technical mitigation potential	[likely to be similar to OAE]	3-30 GtCO2/yr (Köhler et al., 2013; Renforth and Henderson, 2017; Feng et al., 2017; cited in Oschlies et al., 2023 https://doi.org/10.5194/sp-2-oae2023-1-2023) 1-100 GtCO2/yr (Smith et al. 2023; SoCDR) 0.1-1.0 GtCO2/yr (NASEM 2022: A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration) 1-15+ GtCO2/yr (NOAA 2022: Carbon Dioxide Removal Research)	1-3 GtCO2/yr (Smith et al. 2023; SoCDR) 0.1-1.0 GtCO2/yr (NASEM 2022: A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration) 0.1-0.6 GtCO2/ yr (NOAA 2022: Carbon Dioxide Removal Research)	0.1-1.0 GtCO2/yr (NASEM 2022) 1-5 GtCO2/yr (Energy Futures Initiative. “Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments.” December 2020)
Cost (USD/tCO2)	Maybe similar to ERW (50-200/tCO2)	72-159/tCO2 (oceanvisions.org)	25-125/tCO2 (oceanvisions.org)	>100/tCO2 (oceanvisions.org) Significantly larger estimates in NASAEM 2022 (>1000/tCO2)
Actors, activities and projects	**Vesta** (U.S.) Primary research + a CEW pilot (North Sea Beach Colony, Southampton, NY). Goal: (1) quantify rate of olivine sand dissolution in natural setting, (2) document any environmental impacts. NSBC pilot involves the addition of add 500 cubic yards (330 m3) of beach compatible olivine sand to existing permit for the placement of 15,000 cubic yards (11,500 m3) of dredged sand from the North Sea Harbor Inlet.	**Carbon to Sea Initiative** (U.S.) Provides grant funding for research in OAE field (so far >$17M to 4 projects across 8 institutions in America, Asia, Australia and Europe).	**Running Tide** (U.S. / Iceland) [declared bankrupt June 2024] Company developing range of biomass-based technical options through which to cultivate and then sink marine biomass. Three CDR components: 1. Use sustainably sourced biomass to manufacture wood-based floating structures (e.g. buoys) (also impregnated with alkaline materials - see (3)) - (Terrestrial biomass growth and ocean sinking) 2. Deposit structures in marine environment with algae seeding. Algae grow and fix dissolved carbonates from water column. Accumulations of algae cause the structure and biomass to sink, removing the C from the short carbon cycle (Biomass sinking) 3. Alkaline minerals impregnated in wood structures slowly dissolves (Ocean Alkalinisation - see OAE) **Rewind (Israel)** Proposing to sink crop residues to the bottom of the Black Sea, which is reportedly anoxic. Have started small-scale trials in Germany (Selker-Noor), Israel (Sea of Galilee) and in the Black Sea. First scientific report indicates that some degradation of sunk biomass occurred, even in [what was thought to be] anoxic zones. **Seaweed Generation (U.S.)** Focus is on creating technology and infrastructure (automation, robotics) to support the use of macroalgae to remove CO_2. **Seafields Solutions** (U.K.) Cultivating sargassum and sinking to ocean floor.	**Captura Corp** (U.S.) 1. Caltech’s Kerckhoff Marine Laboratory in Newport Beach, CA (1 tCO2 pilot) 2. Marine research facility AltaSea at the Port of L.A (100 tCO2 pilot) 3. Planning 1000 tCO2/yr plant with Equinor (in Norway) **SeaO2** (Netherlands) Planning electrochemical capture methods to remove CO2 from seawater. **SeaCURE** (U.K.) Exeter Uni/EliquoHydrok/Plymouth Marine Lab planning 100 tCO2/year plant in southern England, with UK Government sponsorship. **Ebb Carbon** (U.S.) Works with aquaculture farms, desalination plants, ocean research labs, and other industrial sites that process seawater.

	Coastal Enhanced Weathering (CEW)	Ocean alkalinity enhancement/alkalinisation (OAE)	Ocean fertilisation / Artificial upwelling (AU) / Ocean storage of biomass (OSB)	Electrochemical oceanic carbon removal and storage
Proven efficacy/scalability	Montserrat et al., (2017) demonstrated in laboratory (batch reaction) conditions that olivine dissolution caused a significant increase in alkalinity of seawater with a consequent DIC increase due to CO2 invasion, thereby confirming the viability of the basic concept of enhanced silicate weathering. They also concluded that nonstoichiometric dissolution, potential pore water saturation in the seabed, and the potential occurrence of secondary reactions may will affect quantification in field conditions. Pilot field experiments by Vesta have so far been unable to effectively quantify the efficacy of the CEW process (Coastal Carbon Capture at North Sea Beach. Vesta Annual Monitoring Report: 06/2022 - 01/2023. January 24, 2023)	The ongoing, natural, weathering of rock and the delivery of minerals and bicarbonate to oceans is (ocean alkalinity) is already an important naturally-occurring means of atmospheric carbon removal as part of the Earth's carbon cycle. The ocean presently absorbs around 30% of the CO2 that is released to the atmosphere. As atmospheric CO2 increases, this is reflected by increased levels of CO2 in the ocean. The formation of carbonic acid (HCO3) and its dissociation to H+ (protons) and HCO3 (bicarbonate) causes ocean acidification. The alkalinity process is modulated by the production of carbonate in the ocean, almost exclusively by calcifying marine organisms (NASEM 2022). The carbonate chemistry conditions in the receiving waters are critical to the functioning of calcifying organisms, which are essential for the long-term removal of C from the water column and into oceanic sediments.	Knowledge base for long-term fate of farmed macroalgae is not well-known. Critical that the farmed biomass is stored away the from the surface to ensure sequestration. NASEM (2022) reports that "The long-term incorporation of vast amounts of macrophyte carbon in ocean sediments either by purposeful placement on the seafloor or by sinking seaweed biomass from the surface seems highly unlikely". The cite several studies that examined the fate of sunk biomass in the deep ocean, and note that "the water column seems the most likely reservoir for injected macrophyte carbon".	The efficiency of pumping and removing CO2 from seawater should be compared to the efficiency of the removal of CO2 from air. The added removal action of air-sea gas exchange, relative to DACS, would also feature in oceanic CO2 removal methods .
Factors affecting GHG effectiveness	As for other weathering/mineralisation based processes such as OAE and ERW. **Rate**: Foteinis et al., cite a paper indicating that at 25 °C average, 23 and 700 years, respectively, to dissolve (based on Hangx & Spiers, 2009, International J. GHG Control, 3 (6), 757-767CODEN: IJGGBW; ISSN:1750-5836). Hangz and Spiers, in their study, concluded that for mean seawater temps. of 15- 700-2100 years to reach the necessary steady state sequestration rate and is therefore of little practical value, and that to obtain useful, steady state CO2 uptake rates within 15- The rate of air-sea gas exchange to restore partial pressure can take months to years. Lowering atmospheric CO2 slows the physicochemical uptake of atmospheric CO2 by the ocean, even in some cases possibly causing a small CO2 outgassing [National Academies of Sciences, Engineering, and Medicine (NASEM) 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.] **Materials footprint**: Foteinis et al., (2023) estimated that CEW life- -size olivine) amount to around 51 kg CO2eq per tCO2 removed from the atmosphere (mainly electricity use in rock re less efficient but had lower footprint resulting from lower processing penalties, at 14.2 kg CO2eq tCO2–1 (Environ. Sci. Technol. 2023, 57, 15, 6169–6178; https://doi.org/10.1021/acs.est.2c08633) Hangx & Spiers (2009) concluded that the preparation and major economic, infrastructural and public health questions, indicating that CEW using olivine is not a viable method of CO2 sequestration at scale.	**Rate**: The rate of air-sea gas exchange to restore partial pressure can take months to years. Lowering atmospheric CO2 slows the physicochemical uptake of atmospheric CO2 by the ocean, even in some cases possibly causing a small CO2 outgassing [National Academies of Sciences, Engineering, and Medicine (NASEM) 2022.] **MRV-ability**: difficult to ascertain the extent to which partial pressure equilibrium has been reached. Will require models to estimate as the CO2 flux cannot be directly observed. **Materials footprint**: Several different types of source rocks, including industrial wastes (iron & steel slags; construction waste), may be used to acquire minerals suitable for OAE. The emissions footprint of materials acquisition, processing, transport, and application can therefore be highly variable. Rock (or other source material such as mine tailings or industrial by-products) used to produce ERW and ex situ mineralization feedstocks may be of different grades, with differing yields of suitable silicate-bearing minerals (olivine, serpentine, wollastonite etc), resulting in differing levels of by-product, different types of by-products, differential needs for crushing or grinding processes and different grades of final mineral for application to seawater. **Materials competition**: e.g. with CCU and other types of silicate mineral dependent CDR process (e.g. ERW).	**Rate:** The rate of air-sea gas exchange to restore partial pressure can take months to years. Lowering atmospheric CO2 slows the physicochemical uptake of atmospheric CO2 by the ocean, even in some cases possibly causing a small CO2 outgassing [National Academies of Sciences, Engineering, and Medicine (NASEM) 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.] **MRV-ability**: difficult to ascertain the extent to which partial pressure equilibrium has been reached. Difficult to assess breakdown of organic materials in ocean environment. Will require models to estimate as the CO2 flux cannot be directly observed. **Materials footprint**: source of biomass material will impact overall CO2 reduction. Emissions arising from any conveyance mechanisms used to rapidly transport biomass to deep ocean needs to be taken account of. **Materials competition**: e.g. with CCU and other types of alkali mineral dependent CDR process (e.g. ERW). **Non-permanence/reversal**: risk of decomposition back to CO2, and outgassing form ocean to atmosphere.	As for DACS (removal of CO2 and geological storage) As for OAE (in respect of air-sea gas exchange) Environmental Defence Fund reports that electrochemical ocean CO2 removal: - Requires large quantities of reactants, seawater, and energy. - Removal of 0.001 to 0.002 gigatonnes of CO2 per year (GtC yr-1) electrochemically would require treatment of as much water as currently goes through every desalination plant in the world.64 - Removing just 0.5 (GtC yr-1) per year electrochemically would also require scaling up current worldwide acid production by a factor of about two, or base production by a factor of seven

	Coastal Enhanced Weathering (CEW)	Ocean alkalinity enhancement/alkalinisation (OAE)	Ocean fertilisation / Artificial upwelling (AU) / Ocean storage of biomass (OSB)	Electrochemical oceanic carbon removal and storage
Legal and environmental aspects & safeguards	**Direct**: Environmental impacts may be lower than for ERW, since ERW products may have negative impacts on freshwater environments, which are avoided by direct coastal spreading ('beach nourishment'). **Vesta (U.S.)** pilot monitoring results so far indicated that key water quality parameters within the water column not affected by olivine nourishment. Available post-nourishment ecological trace metal data on Eastern Oyster tissue indicate no trace metal accumulation within soft tissues of this key water quality indicator species. **Compliance with marine pollution protection law:** - Addition of materials to beach environments may fall outside the purview of London Convention. - May be covered by UNCLOS Article 194, 207 and 213 (take measures to reduce and control any source of marine pollution, including land-based source) - Regional seas policies and frameworks may also impact upon eligibility. For example OSPAR convention covers land-based sources of pollution in the North East Atlantic, and others apply to other regions (e.g. Kuwait Protocol, South East Pacific Protocol, Mediterranean Protocol etc.)	**Direct**: Four major groups of OAE/CEW/ERW products: ("alkalinity") (II) Silicic acid (Si(OH)4) "silicate" (III) Certain alkaline earth metals like calcium (Ca2+) and magnesium (Mg2+) but potentially also alkali metals like sodium (Na+) and potassium (K+) (IV) a variety of "trace metals" associated with the minerals. Among these, **iron** (Fe2+, or oxidized aqueous species) and **nickel** (Ni2+) are of concern. These elements occur in high concentrations in basic and ultrabasic rocks (e.g., dunite), which are the most widely recognized source rocks for EW/OAE (Schuiling and Krijgsman, 2006; Hartmann et al., 2013). However, depending on the mineral selected, a wider variety of trace constituents should be considered in the future (from: Bach et al., 2019, Front. Clim. 11 Oct 2019; https://doi.org/10.3389/fclim.2019.00007) Reduced ocean acidification can benefit biodiversity, especially corals and crustaceans (Smith et al, 2023. SoCDR). **Compliance with marine pollution protection law:** - **London Convention**, + 2008 resolution (LC-LP.1) adopted which states that ocean fertilization activities fall within the purview of the LC/LP and that such activities other than legitimate scientific research should not be allowed. + 2010 resolution (LC-LP.2) adopted on the "Assessment Framework for Scientific Research involving Ocean Fertilization," requires that proposed research projects should be assessed to determine if they qualify as legitimate scientific research. + 2013 amendments to LC will, when in force, create a legally-binding regime controlling marine geoengineering techniques (by establishing a formal assessment framework for any materials to be placed into the ocean for the purposes of geoengineering) 2019 GESAMP report concludes that "carbon dioxide removal – geochemical, such as ocean alkalinisation; current knowledge gaps include detection, attribution, upscaling issues and side effects"	**Algal impacts/blooms: Macroalgae known produce methanic substances. U**ncertain risks over uncontrolled algal bloom formation (already a problem in some areas receiving significant agricultural runoff with significant N and P content). **Methane formation and release: D**egradation of biogenic material in anoxic marine environments could leads to CH4 formation. Overturn of stratified water could lead to the release of produced CH4 to the atmosphere or CO2 outgassing, with attendant radiative forcing effects. **Weather impacts:** ocean upwelling and associated ocean surface temperature changes will impact upon Earths weather and climate system (geoengineering). **Compliance with marine pollution protection law:** **- London Convention,** + 2008 resolution (LC-LP.1) adopted which states that ocean fertilization activities fall within the purview of the LC/LP and that such activities other than legitimate scientific research should not be allowed. + 2010 resolution (LC-LP.2) adopted on the "Assessment Framework for Scientific Research involving Ocean Fertilization," requires that proposed research projects should be assessed to determine if they qualify as legitimate scientific research. + 2013 amendments to LC will, when in force, create a legally-binding regime controlling marine geoengineering techniques (2013 amendments to LC will, when in force, create a legally-binding regime controlling marine geoengineering techniques (by establishing a formal assessment framework for any materials to be placed into the ocean for the purposes of geoengineering, under Annex 5).	Discharge water likely to be considered in the same way as that of power plant cooling water. Indeed, most pilot sites are located at power plants.
Geographical, socio-political and other factors	Access rights to utilise international waters to sequester carbon. Allocation of claims (e.g. to national government Parties under the Paris Agreement) for CDR that occurs in international waters	Access rights to utilise international waters to sequester carbon. Allocation of claims (e.g. to national government Parties under the Paris Agreement) for CDR that occurs in international waters	Access rights to utilise international waters to sequester carbon. Allocation of claims (e.g. to national government Parties under the Paris Agreement) for CDR that occurs in international waters	Access rights to utilise international waters to sequester carbon. Allocation of claims (e.g. to national government Parties under the Paris Agreement) for CDR that occurs in international waters

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