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The role of carbon dioxide removal in contributing to the long-term goal of the Paris Agreement

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Preface

This report presents the results of a project commissioned by the Swedish Energy Agency (SEA). The SEA is engaged in turning Article 6 of the Paris Agreement and Rulebook into action, focusing on contributing to international best practice. The long-term temperature target of the Paris Agreement requires the balancing of greenhouse gas emissions by sources and removals by sinks and, furthermore, that legacy emissions are removed by achieving net-negative emissions globally. Carbon market instruments, including Article 6, have the potential to contribute to investments in carbon removal activities.

The report delves into the multifaceted dimensions of carbon dioxide removal methods, and best practices in the implementation of the collaborative instruments under Article 6 for their incentivisation and scaling.

The project has been carried out by Kenneth Möllersten (IVL), project leader, Johannes Bednar (International Institute for Applied Systems Analysis, IIASA), Robert Höglund (Marginal Carbon), Michael Obersteiner (University of Oxford), and Eve Tamme (Climate Principles) during September to November 2023.

List of abbreviations and acronyms

ACR	American Carbon Registry
AFOLU	Agriculture, Forestry, and Other Land Use
AR6	Sixth Assessment Report (of the IPCC)
A/R	Afforestation/Reforestation
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCU/S	Carbon Capture, Utilisation and Storage
CER	Certified Emission Reduction
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CDM	Clean Development Mechanism
CDR	Carbon Dioxide Removal
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
COP	Conference of the Parties
CRCF	(EU) Carbon Removal Certification Framework
CRO	Carbon Removal Obligation
CTBO	Carbon Take-Back Obligations
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
dp-IAM	detailed process-based Integrated Assessment Models
EU ETS	EU Emissions Trading System
EW	Enhanced Weathering
GDP	Gross Domestic Product
GHG	Greenhouse Gas

HFC	Hydrofluorocarbon
HWP	Harvested Wood Product
IAM	Integrated Assessment Model
ICROA	International Carbon Reduction and Offsetting Accreditation
IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal Abatement Cost
MRT	Mean Residence Time
MRV	Monitoring, Measuring, and Reporting
MWP	Mitigation Work Programme
NbS	Nature-based Solutions
NDC	Nationally Determined Contribution
OAE	Ocean Alcalinity Enhancement
OECD	The Organization for Economic Cooperation and Development
SB	(Article 6.4) Supervisory Body
SOC	Soil Organic Carbon
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollars
VCM	Voluntary Carbon Market

Executive summary

This report delves into the multifaceted dimensions of carbon dioxide removal methods. The report discusses the role of carbon dioxide removal methods in contributing to attaining the long-term goal of the Paris Agreement and investigates best practices in the implementation of the collaborative instruments under Article 6 for their incentivisation and scaling. It offers recommendations based on these deliberations.

Shifting focus now from net-zero to net-negative

In 2023, climate policy and actual decision-making are still centred on achieving net-zero carbon emissions predictably leading to a massive climate overshoot (Climate Overshoot Commission, 2023). Countries contributing to over two-thirds of the world's GDP, along with numerous multinational corporations, have committed to reaching net-zero carbon emissions by the middle of this century (Black, et al., 2021; Rogelj, Geden, Cowie, & Reisinger, 2021). However, in view of a dwindling carbon budget that has been exhausted already, or will be during this decade, limiting target setting to net-zero is insufficient. Parties to the United Nations Framework Convention on Climate Change (UNFCCC) need to start taking responsibility to undo their contribution to climate overshoot.

As underscored by the 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC), even if we adopted immediate global emission reduction measures, the 1.5°C mark would probably be exceeded by the mid-2030s. Current greenhouse gas (GHG) emissions continue to rise. The global carbon budget for a 50% chance of staying below 1.5°C has dwindled to 105 GtC from 2023 onwards, equating to roughly nine years at 2022's emission rates (Friedlingstein, et al., 2022). Decarbonizing the global economy before surpassing the 1.5°C threshold demands drastic actions (Grubler, et al., 2018) that are unlikely to be realized in such a limited timeframe. Consequently, by the time net-zero is reached, a significant carbon debt will have been accrued, which will result in overshooting our long-term climate stabilization goals. The extent of this overshoot largely depends on our path to net-zero.

In the short to medium term, Carbon Dioxide Removal (CDR) – henceforth ‘carbon removal’ will play a crucial role in aiding emission reductions, aiming for net-zero carbon emissions by mid-century. Its primary function pre-net-zero is to minimize climate overshoot and avert significant damages and potential Earth system tipping points.

The long-term challenge is to reverse the overshoot. Carbon removal must outpace emissions from sectors that remain challenging to decarbonize in the future (Luderer, et al., 2018), leading to net negative emissions (Gasser, Guivarch, Tachiiri, Jones, & Ciais, 2015). This means extracting more CO_2 from the atmosphere than is emitted. If combined with the reduction of other GHG emissions, this could potentially cool the planet (Fuglestvedt, et al., 2018) and achieve the 1.5°C goal by 2100, even with a temporary overshoot. However, a net-negative economy could strain governmental finances, as carbon taxes on fossil fuels may not generate enough revenue to support large-scale carbon removal (Bednar, Obersteiner, & Wagner, 2019).

Addressing the financial constraints and factoring in fairness across generations, it's evident that the creation of a carbon debt and commitments to overshoots begin with every emission today and not just after exhausting the carbon budget. Thus, plans to manage the overshoot, including securing a lasting net-negative carbon economy, should start soon, certainly before the carbon budget is depleted in the upcoming decade. Essentially, preparing for a net-negative economy involves extensive deployment of carbon removal throughout the century. This sharply contrasts with the current net-zero-focused policy that emphasizes emission reductions and views carbon removal as a way to perpetuate the fossil fuel era. To genuinely prevent an overshoot, we need both aggressive emission reductions and large-scale deployment of a range of CDR methods.

To manage the overshoot, there are vital questions that need answers, e.g.,: When does the overshoot commence and who holds the responsibility for the overshoot and its associated instantaneous and historical emissions? Who will finance the overshoot reversal using large-scale deployment of carbon removal? What economic repercussions are associated with an overshoot and potentially excessive costs for large-scale carbon removal? What political challenges might arise, especially when considering a potential financial infeasibility of reversing physical overshoots just as climate impacts peak, making funding for carbon removal less probable?

All these issues can be addressed by a well-designed policy and governance framework constructed around a Carbon Removal Obligation (Bednar, et al., 2023).

Characterising carbon dioxide removal methods

The report outlines the concept of carbon removal as a key strategy for climate change mitigation. IPCC defines CDR methods as human activities that remove CO_2 from the atmosphere and store it durably. Carbon removal primarily focuses on CO_2 removal, although removal of other GHGs is considered in the broader concept of GHG removal. The three main roles of CDR are to lower net CO_2 emissions in the short to medium term, offset challenging residual emissions to enable net-zero and achieve net negative CO_2 or GHG emissions in the long term.

Various CDR methods are categorized based on capture and storage processes. Capture methods encompass biological, geochemical, and chemical approaches, while storage occurs in land-based, product-based, and geochemical media. Notable methods include afforestation, biochar carbon removal, bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced weathering (EW), and ocean alkalinization.

Many conventional CDR methods that have reached relative maturity are found in the land use sector, i.e., carbon removal within Agriculture, Forestry, and Other Land Use (AFOLU). These so-called Nature-based Solutions (NbS) include, *inter alia*, afforestation, reforestation, sustainable forest management, and wetland restoration, acting by combinations of carbon pool conservation and enhanced carbon removal. Although the main focus in carbon crediting schemes in this space has been on emission reductions, the dual mitigation impact has been taken into account by some methodologies, sometimes involving difficulties in differentiating emission reduction credits from removal credits. There are ongoing efforts to differentiate and label emission reduction credits from removal credits.

Carbon sequestered through NbS methods, such as reforestation or wetland restoration, is susceptible to reversal due to both natural disturbances and human activities and reach saturation. Combined NbS with novel biomass-based CDR methods outperforms pure NbS in the long run, maximising carbon sequestration by both rejuvenating forests and preventing biomass decay.

Carbon dioxide removal in the context of the Paris Agreement

The Paris Agreement has three areas of implementation that are relevant for carbon removal – the international carbon markets under Article 6, the global stocktake, and the mitigation work programme (MWP). Article 6 covers emission reductions and carbon removals and is technology-neutral in its approach, its scope is not limited to specific carbon removal methods. While the cooperative approaches under Article 6.2 are already operational, removals have yet to establish a notable role in the bilateral agreements. In November 2023, the Supervisory Body of the Article 6.4 mechanism approved the recommendations on methodologies and activities involving removals, proposing the foundation for how removals will be included in the international carbon crediting mechanism. If adopted at CMA5 during COP28, the Article 6.4 mechanism would finally become operational.

The global stocktake is a process for countries and stakeholders to see where they are collectively making progress towards meeting the Paris Agreement goals. It is an opportunity to highlight the role of carbon removal, the need to align financial flows to scale up CDR methods, and the need for a more detailed representation of carbon removal in nationally determined contributions (NDCs) in the upcoming CMA decision. Another stream of work, the MWP, encourages countries to align their targets and actions towards net-zero in a manner that complements the global stocktake. Given the progress to date, the temporary nature and lack of ambition of the MWP, it is less likely to provide meaningful guidance on removals compared to the global stocktake and Article 6.4.

Carbon removals and carbon markets in the literature

The literature on using carbon markets to incentivise carbon removal is somewhat limited, albeit growing at a fast rate. Since countries have different capacities for net-negative emissions and varying amounts of residual emissions, trading under Article 6 will likely be necessary to incentivize countries with excess capacity to go net-negative to balance out remaining emissions from countries without the ability to mitigate to net-zero. Carbon removal in the Article 6 market mechanisms is also seen as a tool for addressing equity in large-scale carbon removal.

Financing novel carbon removal via Article 6 is challenging due to significant upfront capital and near-term operating expenses for novel CDR methods. There is a need to bridge the gap between the market price and the cost level of the technologies.

The questions around the environmental integrity of conventional removals lead to conclusions that emissions should be offset with like-for-like carbon removal, with CO_2 from fossil fuel sources balanced with geological storage. Conventional carbon removal would be best suited to addressing land-use emissions or short-lived GHGs.

Separate targets for emissions reduction and carbon removal would allow responsible incentivising of carbon removal deployment. As global emissions approach zero on the way to net negative emissions, international market-based cooperation under Article 6 will, over time, increasingly shift focus from emissions reduction activities and have a new and different role in carbon removal activities.

Literature-based cost comparison

The text report explores and compares the cost of emission reduction and carbon removal. Key factors influencing the decision to use carbon removal over emission reductions include cost considerations. The IPCC's Sixth Assessment Report (AR6) estimates the costs and potential of various emission reduction measures until 2030, indicating that emission reduction options vary in cost as they are deployed. The costs range from zero for certain measures to higher values for technologies like carbon capture and storage. Costs of carbon removal are presented derived from a literature review encompassing over 40 studies from 2017 to 2023. These estimates provide insights into the future costs of carbon removal. While emission reduction measures generally appear to be more cost-effective than novel CDR methods, a significant portion of emission reductions on the higher end of the marginal abatement cost (MAC) curve face costs exceeding those of carbon removal. MAC for limiting global warming to 1.5°C or 2°C also surpass the costs of CDR methods.

Contrasting emission reductions vs. carbon removals using scenarios

The report uses four illustrative climate mitigation scenario ensembles, aiming to curb carbon emissions and achieve global net-zero CO_2 emissions within a specific timeline. The scenarios are:

Proactive Transition: Characterised by swift displacement of fossil fuels with primary energy substitutes like biomass, nuclear, and non-biomass renewables. Strong focus on curtailing final energy demand and achieving tangible emission reductions. Heavy deployment of Carbon Capture and Storage (CCS) and carbon removal. This scenario ensemble creates the least climate overshoot compared to other scenarios.

Gradual Realisation: Similar ambitions to replace fossil fuels with alternatives as in the Proactive Transition scenario. Initial emphasis on emission reductions, with later recognition of the importance of CCS and carbon removal. This scenario creates a notable climate overshoot due to the delayed integration of carbon removal and CCS.

Unified Market Approach: Integrates a single market system where a unified price covers both carbon removal and emission reductions. Enables trading of "removal units" akin to emission reduction certificates. The scenario raises concerns about potential overshoot due to delayed emission reductions in favour of future carbon removal.

Delayed Decarbonisation: Defers decarbonisation efforts by a decade, resulting in a significant temperature overshoot. Heightened focus on carbon removal, especially DACCS, to counterbalance the delay.

All scenarios converge towards a temperature rise between 1.5 to 1.7°C in the long term and they exhibit some shared traits: Unparalleled emissions reductions and substantial carbon removal are required. In all scenarios, emission reductions and curbing final energy demand precede other strategies indicating a clear mitigation hierarchy. Sequestration (CCS applied in the contexts of fossil emissions and carbon removal, respectively) through various methods plays an essential role.

The study also delves into regional representations based on the IPCC’s R10 region specifications and explores the potential for regions to act as carbon removal exporters or importers based on different burden-sharing arrangements.

Several conclusions are drawn in terms of mitigating deterrence:
- Metrics used in relation to mitigation deterrence matter.
- Full fungibility between emission reductions and carbon removals, or a lack of rigorous regulation can induce various types of deterrence through the use of CCS and carbon removals. It is imperative to establish distinctly separate policy frameworks for emission reductions and for carbon removals and to limit fungibility between emission reductions and carbon removal.
- Incentivizing a near-term ramp-up of CCS and CDR technologies is essential to ensure the attainability of ambitious climate goals and peak-shaving of the near-term overshoot.
- It is essential to manage climate overshoot by setting near-term targets (e.g. GHG concentration target) and ensuring accountability and responsibility for delayed removals.
- Managing low-integrity carbon removals through the principle of like-for-like removal is recommended.
- Positive and negative externalities of emission reductions and carbon removals should be accounted for in the design of bespoke policy instruments.

Applying a broader perspective, the study discusses barriers and trade-offs for CDR methods, categorizing them into conventional NbS and novel CDR methods.

NbS encounter challenges in land tenure, property rights, lack of awareness, and potential social and environmental trade-offs etc. Robust institutional frameworks and comprehensive environmental assessments are needed for effective NbS deployment at scale. Novel CDR methods, including DACCS and BECCS, face barriers such as energy intensity, prohibitive costs, land and water competition, and technological integration challenges. Coordination and regulatory support are vital for successful deployment. Ocean Alkalinity Enhancement (OAE) and enhanced weathering present nascent but promising technologies, albeit with logistical, environmental, and regulatory hurdles. The development of methods for monitoring and certification is crucial for scaling these technologies.

CDR methods and risk of reversal and leakage

The report explores risks of reversal and carbon leakage associated with carbon removal. It discusses the durability of carbon storage for various storage processes. Carbon storage durability is often talked about as permanent or temporary, but in this report a more nuanced vocabulary is proposed. Storage longevity is classified into categories like permanent storage, stable storage, long-term temporary storage, vulnerable storage, and short-term temporary storage. The ‘expected storage time’ concept considers the risk of reversal and gradual re-release of carbon. Short-lived and permanent carbon storage are compared, emphasizing the need for carbon storage to last beyond peak temperatures to be effective.

Carbon leakage (a type of ‘spillover effect’) is defined as the indirect net change in GHG emissions or carbon removals attributable to a mitigation activity occurring outside its boundary. The definition of leakage comprises that the leakage-affected outcome variable is the same as the targeted outcome of the intervention and has a negative (counteracting) effect on this variable. Different types of leakage are identified, including strong and weak leakage, activity leakage, land market leakage, commodity market leakage, and supply chain leakage. The discussion highlights the complexities in particular of governing land use and the challenges of accurately measuring leakage, especially when economic markets are involved.

Mapping and analysis of approaches to manage risk of reversal, carbon leakage and monitoring of carbon removal

Durability and leakage provisions in existing and upcoming carbon crediting programs are mapped. Forest sector sequestration tends to have shorter durability, contrasting with other methods like geological storage or biochar, which offer longer durations, even up to permanent storage. Durability mechanisms such as commitment periods, risk management frameworks, and buffer provisions help manage the reversibility risk associated with carbon removal projects.

Leakage, referring to emissions indirectly caused by a project activity, is a crucial consideration. Various carbon crediting programs incorporate leakage provisions, employing different approaches to quantify, mitigate, and account for leakage emissions. For example, Verra and ACR have methodology-specific leakage management, while the CDM emphasizes minimizing leakage in A/R projects.

The text also considers emerging carbon crediting programmes/frameworks: the European Union Carbon Removal Certification Framework (CRCF) and the Article 6.4 Mechanism. The CRCF emphasises durability based on the storage type and addressing reversals through liability mechanisms. Discussions regarding risk assessment, reversal management mechanisms, and leakage provisions in the ongoing development of the Article 6.4 Mechanism are summarised.

The report, furthermore, discusses considerations related to the risk of reversal, leakage, and monitoring in the context of removals guidance.

Risk of Reversal: Strategies to mitigate the risk of reversal can be framed as supplier obligations involving replacing reversed carbon through renewing credits or using physical buffer pools. However, estimating adequate buffer pool sizes and ensuring their long-term effectiveness can be challenging. Buyer obligations can replace reversed carbon through periodic repurchasing or insurance-style models. Shifting the replacement obligation to the government entity after a certain period is an option, spreading responsibility and avoiding reliance on private entities. There are challenges embedded in managing the risk of reversal for carbon removal credits and convincing solutions that work across the board are lacking. The "like-for-like" principle emphasises using carbon removals with durability matching the emissions' lifetime for specific offsetting purposes and can be used to complement permanence and reversal management mechanisms. For offsetting a specific CO_2 emission to prevent increased warming, the removal needs to have durability matching the emission's lifetime, favouring long-lived or permanent storage. Continuously offsetting short-lived climate pollutants doesn't require permanent storage. Addressing historical CO_2 emissions or contributing to overall CO_2 reduction without linking to a specific emission allows for non-permanent but long-lasting storage, provided robust provisions ensure replacement upon reversal.

Addressing Leakage: Addressing spillover and leakage effects requires comprehensive accounting across sectors and activities. The attribution of spillover to a specific intervention is challenging due to various drivers of land use change. Identifying conditions that make places susceptible to leakage helps improve policy design. Leakage can be underestimated, and current efforts to improve accounting methods may not suffice. One proposed approach is to use upper-bound estimates of potential leakage when designing nature-based interventions subject to the risk of market leakage.

Monitoring: Monitoring, reporting, and verification (MRV) are crucial for carbon accounting and GHG liability. The feasibility of MRV varies among different CDR methods, with each method requiring specific MRV protocols. The simplicity and precision of quantifying carbon removal and storage differ across CDR methods, and existing MRV methodologies vary in availability. Existing MRV rules for most conventional NbS already exist at national and project levels through the IPCC Guidelines for National Greenhouse Gas Inventories and various project certification methodologies. Several novel CDR methods require significant progress before robust MRV is possible.

Recommendations

Based on the analysis performed the following recommendations are offered. It is recommended that:

- Responsibility for climate overshoot reversal must be given immediate attention in the climate talks as the sum of climate pledges will create a sizeable overshoot. A well-structured governance system regulating the implementation of a politically negotiated burden-sharing arrangement is needed to guarantee the viability of a global net-negative GHG economy to emerge within the next three decades.

-Mitigation policies must build on separate short- and long-term targets for emission reductions and carbon removals to contain the risk of mitigation deterrence. Such a separate targets strategy should consider a near-term overshoot target that incorporates early and radical emission reductions with simultaneous near-term development and ramping-up of CDR methods to clarify their actual potentials and the scaling properties of specific technological options. In the medium-term perspective, a policy design that separates the promotion of large-scale deployment of carbon removal technologies from emission reduction policies will ensure that reductions of abatable emissions are complemented and not crowded out by CDR. By advocating for the early integration of CDR (which would benefit also from a more general development of Carbon Capture and Storage), technological learning is enhanced, and economies of scale are realized, allowing for a gradual decline in cost over time. This is vital to reduce the extent of the overshoot and its inherent risks as well as to achieve net-zero timely.

-Policies for the promotion of carbon removals should incorporate risk-mitigation strategies aiming at the long-term goal of ensuring permanence by combining NbS with novel biomass-based CDR methods.

-Policies must be designed to limit the fungibility between emission reduction and carbon removal mitigation outcomes in emissions trading. This should include provisions that limit the extent to which carbon removals that are over-proportionally cost-competitive and do not have very long-lived or permanent storage are allowed to be used for offsetting fossil CO_2 emissions.

-When the design of nature-based carbon removal interventions implies market leakage risks, upper-bound estimates of potential leakage should be used. Furthermore, nature-based credits which include market leakage risk in their design should not substitute for emission reductions in compliance settings.

-Monitoring, Reporting, and Verification (MRV) protocols should consider the feasibility of MRV for the capture and storage steps separately. MRV protocols will be specific to individual CDR methods, and to some extent context. Some novel CDR methods need much further development before MRV can be applied with respect to mitigation outcomes and in some cases potential side effects. This implies restrictions concerning their use for offsetting.

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1 Introduction

1.1 Aim and problem formulation

The Swedish Energy Agency commissioned this study which is to delve into the following topics:

(i) The efficiency, inherent risks, and economic feasibility of various Carbon Dioxide Removal (CDR) methods compared to emission reductions as well as to draw conclusions regarding their potentials.

(ii) The potential evolution of the global and regional balance of emissions and different categories of removals over time.

(iii) The scope and focus of major standards for results-based payments and/or crediting that cover CDR as well as approaches applied by standards for the consideration of durability of carbon storage and leakage, including their applicability to different CDR methods.

(iv) The role and potential of carbon markets in incentivising and scaling CDR.

(v) An investigation into the economic underpinnings of the Carbon Removal Obligation (CROs) framework.

As per the Terms of Reference (ToR), there is a need to delve into the multifaceted dimensions of CDR methods, and best practices in the implementation of the collaborative instruments under Article 6 for their incentivisation and scaling. This report henceforth refers to CDR as “carbon removal” (while the term “CDR method” is maintained). The proposed work is to include a comparative analysis both internally among CDR methods and between emission reductions and carbon removal in order to identify factors affecting the comparability of the contribution of emission reductions and carbon removal to the achievement of the goals of the Paris Agreement. This analysis is to consider the durability and reliability of different categories of carbon removals and vulnerabilities to the impacts of climate change. Furthermore, factors that affect the actual realisation of CDR methods’ technical potentials shall be highlighted as this would provide additional nuances providing support for the interpretation of model-based mitigation scenarios.

The study shall, furthermore, provide a more theoretical background on leakage applicable to land-based CDR methods (with a primary focus on land use-based activities), including categorisation and possibilities and challenges in relation to prediction and detection of leakage. In relation to risk of reversals, the scope of the study includes a review and summary of proposed approaches in the literature and under consideration in ongoing policy discussions, to be considered alongside approaches identified through the mapping of major standards.

Aspects related to crediting mechanisms and monitoring, reporting, and verification warrant analysis and resolution. Important considerations that will be considered in the study include measurability vs. model-based estimates and the transparent characterisation of, inter alia, short-term versus long-term CO_2 storage to encourage and internalise differences in quality and durability of carbon storage in MRV protocols.

The assignment aims (in accordance with the ToR) at utilising findings from the analyses made to assess:

- Scenarios for the likely timing and level of deployment of different categories of removals to offset emissions through the international carbon market.

- Scenarios for the potential evolution of the global and regional balance of emissions and different categories of removals over time.

- Recommendations with respect to scope and focus of removals guidance, including priorities in the development of guidance.

1.2 Background

Scenarios limiting global warming to close to 1.5°C by 2100 included in the IPCC AR6 WGIII report (IPCC, 2022) require that net-zero CO_2 emissions are reached globally by mid-century. In addition to rapid and deep greenhouse gas (GHG) emission reductions, scenarios also rely on large volumes of carbon removal. Carbon removal is necessary to achieve the two main functions of (i) counterbalancing of hard-to-abate residual emissions - a fundamental requirement to attain global net-zero CO_2 or GHG emissions - and (ii) achieving globally net-negative emissions in order to reduce peak cumulative net CO_2 emissions (“legacy carbon removal”) and cause a decline in CO_2 induced warming. The latter can be achieved through eventually reaching a state at which CDR rates exceed the rate of residual emissions as originally proposed by Obersteiner et al. (2001a). CDR methods, i.e., anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products, add to the array of GHG mitigation options. In addition to the two main functions already mentioned, carbon removal may enable faster lowering of net CO_2 or GHG emissions on the shorter term, and to enhanced cost-effectiveness of achieving GHG mitigation targets from regional to global scales.

Minimum requirements of carbon removal contributions until 2100 are measured in hundreds $GtCO_2$ with annual removal rates at the end of the century reaching nearly 50 percent of current global annual GHG emissions (IPCC, 2022). A portion of the required carbon removal can be achieved through nature-based solutions (NbS), for example afforestation and various kinds of ecosystem restoration ("conventional land-based CDR"). However, to attain the CDR rates likely required later this century, significant contributions from different kinds of so-called (less mature) "novel CDR methods" (e.g., bioenergy with carbon capture and storage, BECCS and direct air carbon capture and storage, DACCS, will be required. The current rate of carbon removal through "conventional CDR methods" (building on NbS) is around 2 $GtCO_2$/yr and from novel CDR methods around 2 $MtCO_2$/year (Smith, et al., 2023). The magnitude of required future carbon removal thus presents a remarkable scaling challenge. This implies technical, environmental, and financing challenges as well as socio-economic opportunities and risks that need to be thoroughly assessed to attain a good understanding of their potential for implementation. Analysis of performance, opportunities and risks of CDR methods are in many ways sensitive to regional context and specific technological configurations (Fuss, et al., 2018; Honegger, Michaelowa, & Roy, Potential implications of carbon dioxide removal for the sustainable development goals, 2021; Möllersten K. , 2022).

Widespread optimism about the potential of CDR (such as BECCS and other methods) later in the century has led to concerns that the prospect of future carbon removal may lead to over-reliance on CDR methods that may prove not to be scalable (Obersteiner, et al., 2017). Separate targets for emission reductions and carbon removal have been proposed as a way to manage the risk of less emphasis on fossil fuel mitigation due to the predicted future availability of carbon removal (known as "mitigation deterrence") (McLaren, Tyfield, Willis, Szerszynski, & Markusson, 2019; Morrow, et al., 2020). Bednar et al. (2019) proposed that a mitigation strategy should build on two pillars:

(i) earlier and more radical reductions in emissions than what most Paris Agreement-compliant mitigation scenarios (most of which already relying on vast carbon removal contributions) suggest; and

(ii) near-term development and ramping-up of "Negative Emission Technologies" to clarify their actual potentials and the scaling properties of specific technological options.

Hence, policy is needed that is sufficient to trigger the required decarbonization while also creating sufficient incentives for large-scale demonstration and gradually elevated deployment of carbon removal. International carbon markets are potentially a powerful tool for mobilizing carbon removal in line with Paris Agreement ambitions. Carbon markets, including voluntary carbon markets (VCM), also have the potential to create early market signals and funding, and support diffusion of CDR technology, thereby supporting development and deployment of carbon removal technology (Allen, et al., 2020). Driven by high prices for carbon credits from novel CDR methods various newcomers in VCM are currently establishing their own methodologies for generating carbon removal credits. However, markets for carbon removal credits are still immature and challenged by inconsistent approaches to measurement, reporting, and verification (MRV) of mitigation outcomes.

Prerequisites for realising net-negative carbon futures require special attention. Currently envisaged carbon tax schemes would turn into public subsidies under net-negative emissions with potentially prohibitive fiscal implications (Bednar, et al., 2019). Addressing this challenge, Bednar et al. (2021) proposed a new type of intertemporal instruments - carbon removal obligations (CRO) - where the polluter pays principle is deployed to ensure near-term emitters remain liable for CDR further in the future.

2 Methodology

The methodology used for this report is based on (i) literature review, (ii) modelling experiments utilizing a state-of-the-art reduced complexity computer model, harmonized with the detailed process-based Integrated Assessment Models (dp-IAMs) outlined in the AR6 of the IPCC, and (iii) application of the authors' expert judgement.

The literature review was performed thematically to cover the main topics outlined in section 1.1. For each topic search queries were defined, keyword searches performed using the search engine Google Scholar, studies were then individually screened for relevance and quality, and qualitative and quantitative evidence was extracted and synthesized from the final document set.

The modelling section presents four illustrative global mitigation scenarios, contrasting their emissions reduction and removal potentials, costs, timing, and regional patterns. These scenario narratives are designed to provide concrete quantifications of mitigation deterrence and its most relevant drivers.

For each thematic area gathered information has been assessed by a subset of authors with the corresponding expertise, considering our current understanding of the literature and the evolving policy landscape.

Final policy recommendations were structured and refined by the authors in an interactive workshop.

The initial project proposal has been reviewed and commented upon by a reference group consisting of EU Article 6 experts. The same reference group also reviewed and commented upon a draft of the final report.

3 Characterising carbon dioxide removal methods

3.1 Definition and role

The IPCC defines CDR as a collective term for "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products (. . .)” (IPCC, 2022). CDR and removal of other GHGs are forms of climate change mitigation in accordance with UN climate governance (Honegger, Burns, & Morrow, Is carbon dioxide removal ‘mitigation of climate change’?, 2021). Although removal methods for other GHGs than CO_2 have been discussed (IPCC, 2022), carbon dioxide removal remains the focus.

As part of mitigation strategies at global or sub-global levels, carbon removal can fulfil three different roles in complementing emission reductions: (i) lowering net CO_2 emissions in the near- to medium term; (ii) counterbalancing hard-to-abate residual emissions like diffuse CO_2 emissions from industrial activities and methane and nitrous oxide emissions from agriculture, in order to help achieve net-zero emissions and (iii) achieving net negative CO_2 or GHG emissions in the long-term if deployed at levels exceeding residual emissions. Net-negative emissions enables a reduction in peak cumulative net CO_2 emissions and can, thus, be used to force a decline in CO_2-induced warming.

CDR methods were originally identified as a risk management tool for climate mitigation (Obersteiner M. , et al., 2001a; Obersteiner M. , et al., 2001b) in cases where (i) Earth system feedback leads to additional unanticipated GHG emissions (Gasser, et al., 2018), (ii) (un-)intentional failure by one Party to achieve necessary emission reductions can be compensated by the negative emissions by another Party (iii) Failure to set robust climate mitigation targets which will need to be adjusted over time to ensure Earth system security and intergenerational equity (iv) Failure of a promising technology to deliver the expected emission reduction outcomes.

Due to the fact that Integrated Assessment Models (IAMs) used for the IPCC climate mitigation assessment are of deterministic character these climate mitigation risk management function of CDR methods has been largely ignored and CDR methods were over time implemented in these scenario exercises as regular emission reduction technologies to reach gradually more ambitious climate targets including the scenarios supporting the formulation of the Paris Agreement.

3.2 Capture and storage processes

There is a variety of CDR methods and categorisation of methods can be based on several criteria (IPCC, 2022). The removal can be land-based biological; ocean-based biological; geochemical or chemical and the storage takes place in different carbon storage media that represent storage at timescales that vary between decades to centuries; centuries to millennia; or longer. Capture and storage processes can be divided into the below categories (based on Smith et al., (2023)):

3.2.1 Capture processes

- **Biological capture** takes place through photosynthesis, CO_2 is taken up from the atmosphere by trees, crops, and aquatic biomass such as kelp and seagrasses.

- **Geochemical capture** occurs via a range of minerals binding atmospheric CO_2, including naturally occurring minerals in rock and alkaline waste materials from construction and industry. The CO_2 is bound in the form of solid carbonate (which can be used as a product, such as aggregates) or dissolved bicarbonate, both of which are durable carbon pools.

- **Chemical capture** is when CO_2 can is captured directly from air using chemical solvents and sorbents designed to re-release it as a concentrated CO_2 stream for use or storage.

3.2.2 Storage processes

- **Biological storage** (on land and in oceans). Trees can retain their carbon for decades, centuries or more. Soils and wetlands are a further store of carbon, derived from compounds exuded by roots and dead plant matter. In the oceans, aquatic biomass may sink to the ocean floor and become marine sediment. Carbon can be retained durably in these ecosystems, especially if managed carefully to reduce disturbances.

- **Product storage**. Some carbon-based products constitute durable storage. For example, construction materials and biochar can store carbon for decades or more.

These carbon-based products can be made from conversion of harvested biomass (in the cases of biochar and wood in construction), from concentrated CO_2 streams or even from CO_2 from ambient air (in the case of aggregates).

- **Geochemical storage**. Concentrated CO_2 can be stored in geological formations, using depleted oil and gas fields or saline aquifers, or reactive minerals such as basalt. Geochemical capture leads directly to long-term storage of CO_2 in the form of carbonate minerals or bicarbonate in the ocean.

Different carbon pools have very different characteristic timescales for storage and risks of reversal which is further addressed in section 8.

3.3 Main CDR methods

Table 1 describes main CDR methods by the route of CDR, i.e., how CO_2 is captured and how carbon is stored to prevent the re-release of CO_2 to the atmosphere. One CDR method is not one single technological design/solution (Möllersten & Naqvi, 2022) and options often differ within one CDR method with respect to dynamic or context-specific dimensions such as mitigation potential, cost, potential for co-benefits and adverse side-effects, and technology readiness level (IPCC, 2022).

System boundaries need to be carefully considered when evaluating the efficiency of CDR methods (mitigation efficiency, economic efficiency etc.) Gross CO_2 removal from the atmosphere, as the outcome of deliberate activities implementing CDR options, differs from the net emissions outcome achieved (i.e., gross emissions minus gross removals). The following example serves to highlight the significance of system boundary selection: IEAGH (2021) converted cost estimates for an existing direct air carbon capture installation (DACCS), at 600–700 USD/t$CO_{2,\text{captured}}$ on a "gross CO_2 removed" basis, to cost of CO_2 removed on a net basis assuming energy supply from a natural gas fired plant, resulting in costs in the range 1100-1500 USD/t $CO_{2,\text{removed}}$.[1]

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[1] These estimates exclude the cost of compression, transportation and storage.

Table 1 Summary of Carbon Dioxide Removal (CDR) methods and the route through the carbon cycle that they employ. Based on IPCC (2022); Smith et al., (2023); NASEM (2018).

CDR method	**Route of carbon removal**	
	Capture process	**Storage process**
Afforestation/ Reforestation, including agroforestry and improved forest management	Biological capture via trees	Storage in trees
Durable Harvested Wood Products	Biological capture via trees	Storage in wood in construction
Soil carbon sequestration	Biological capture via various agricultural practices and pasture management	Storage in soils
Biochar carbon removal	Biological capture via cropping and forestry residues, organic wastes, or purpose-grown crops	Storage in biochar
BECCS (Bioenergy with Carbon Capture and Storage)	Biological capture via plant growth	Concentrated CO_2 -> Storage in lithosphere
DACCS (Direct Air Carbon Capture and Storage)	Chemical capture via solid sorbent or liquid solvent	Concentrated CO_2 stream -> Storage in lithosphere
Accelerated mineralisation	Biological capture via plant growth	Storage in minerals
Enhanced rock weathering (EW)	Geochemical capture via spreading crushed silicate rocks on land or ocean	Storage in minerals or as bicarbonate
Peatland and wetland restoration	Biological capture via rewetting and revegetation	Storage in soils
Coastal wetland (blue carbon) management	Biological capture via aquatic biomass	Storage in aquatic biomass
Ocean alkalininity enhancement	Geochemical capture via adding alkaline materials to the ocean such as silicate or carbonate rocks	Storage in minerals or as bicarbonate
Ocean fertilisation	Biological capture via fertilisation or enhanced upwelling	Storage in marine sediment

3.3.1 Unpacking carbon removal in AFOLU mitigation measures

AFOLU mitigation are a variety of land management practices that reduce GHG emissions and/or enhance carbon removal within the land system (i.e. in forests, wetlands, grasslands, croplands and pasturelands).[2] The summary below is limited to forests and other ecosystems and based mainly on IPCC (2022).

Reducing deforestation and forest degradation conserves existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance and is, consequently, mainly focused on emission reductions. Protecting forests involves controlling the drivers of deforestation and forest degradation, as well as by establishing well designed, managed and funded protected areas, improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification.

Afforestation and reforestation (A/R) are activities that convert land to forest, thus contributing to capture of atmospheric CO_2 via biological capture. Reforestation occurs on land that has previously contained forests, while afforestation is on land that historically has not been forested. Forest restoration refers to a form of reforestation that gives more priority to ecological integrity as well, even though it can still be a managed forest.

Improved sustainable forest management of already managed forests can lead to higher forest carbon stocks, thus delivering CDR by the same capture and storage processes as A/R and can also partially prevent and counteract the impacts of disturbance.

Reducing the conversion of grasslands and savannas to croplands prevents soil carbon losses by oxidation, and to a smaller extent, biomass carbon loss due to vegetation clearing. For increased soil organic matter in grasslands, practices include management of vegetation, livestock management and fire management.

Reducing the conversion of peatlands avoids emissions of above- and below-ground biomass and soil carbon due to vegetation clearing, fires, and peat decomposition from drainage. Similar to the case of deforestation, peatland carbon stocks can be conserved by controlling the drivers of conversion and degradation and improving governance and management. Peatland carbon stocks accumulate slowly and persist over millennia

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[2] Implemented with benefits to human well-being and biodiversity, land-based mitigation measures are often referred to as nature-based solutions and/or natural climate solutions (Griscom, et al., 2017).

and loss of existing stocks cannot be easily reversed over the decadal timescales needed to meet the Paris Agreement.

Peatland restoration involves restoring degraded and damaged peatlands, for example through rewetting and revegetation, which both increases carbon accumulation in vegetation and soils and avoids ongoing CO_2 emissions. Restoring the wetland hydrology and perennial vegetation can reverse the processes driving soil carbon losses and greatly reduce CO_2 losses compared to drained organic soils and in many cases re-establish the carbon sequestration capacity. While reducing the conversion of wetlands provides emission reductions, peatland restoration delivers both emission reductions and carbon removal.

Reducing conversion of coastal wetlands, including mangroves, marshes and seagrass ecosystems, avoids emissions from above and below ground biomass and soil carbon through avoided degradation and/or loss. Coastal wetlands are extremely productive ecosystems; they act as long-term carbon sinks by removing carbon from the atmosphere through photosynthesis and storing it in their soils for long time periods. Compared to other ecosystems, coastal wetlands, such as salt marshes and mangroves, are extremely productive and sequester a very high amount of carbon per unit area (NASEM, 2018). Coastal wetland restoration leads to sequestration of so-called ‘blue carbon’ in wetland vegetation and soil. However, loss of existing stocks cannot be easily reversed over decadal timescales.

As already pointed out, schemes for the promotion of reducing emissions from deforestation and forest degradation, improved forest management and sustainable agricultural management can encompass both emission reductions and carbon removal. Although the main focus in carbon crediting schemes has been on emission reductions, the dual mitigation impact has been taken into account by some methodologies. Difficulties in differentiating emission reduction credits from removal credits have been identified (Michaelowa, et al., 2023). The American Carbon Registry is currently developing tools for properly differentiating and labelling removal and emission reduction credits in improved forest management project activities. The Verra standard will differentiate between emission reduction and removal credits in 2023[3].

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[3] https://verra.org/verra-publishes-responses-to-consultation-on-proposed-vcu-labels/

3.4 Dynamic comparison of Nature based solutions and (engineered) novel CDR combinations

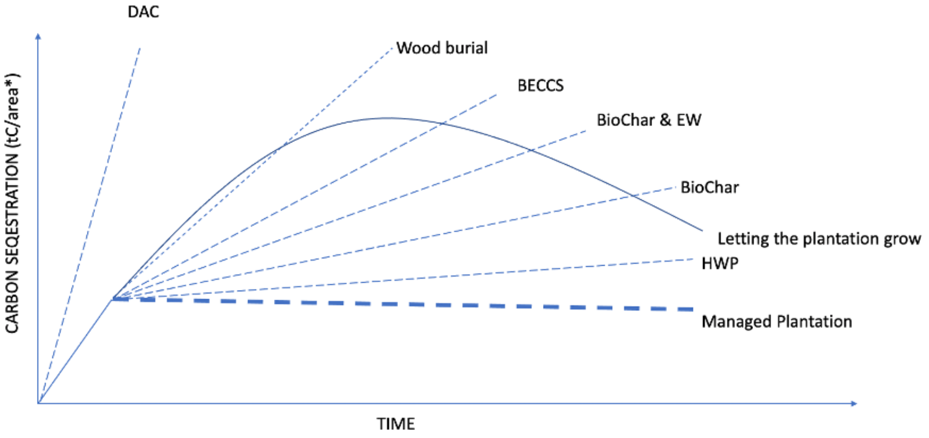

Figure 1: Illustrative example of carbon sequestration of different CDR methods over time. We compare different CDR method combinations that assume different uses of harvested biomass from a managed tree plantation to the reference case of allowing the plantation to grow. The lower thick dashed line depicts the evolution of carbon sequestration of a tree plantation under harvesting. For benchmarking reasons, we assume a scenario where we allow the plantation to grow without harvesting and assume a decline in the plantation stocks after 2-3 rotation periods due to natural forest die-back. We then make assumptions about different novel CDR methods which make use of the biomass from the plantation. The first case depicts the case of harvested wood products (HWP) where we assume a relatively low wood utilization share and most of the wood enters a short-term storage HWP pool. In the most extreme case where all of the wood is used as construction material (incl. compressed saw dust) the HWP line could become identical to the uppermost line assuming wood burial. The next wood utilization scenario assumes the production of biochar at a relatively low efficiency and where all of the resulting gases are vented unabated to the air. In case of a biochar production facility that is combined with BECCS the biochar line could be close to the BECCS line. We have also added a combination of Biochar with enhanced weathering, where we assume that the biochar is mixed with rock-powder providing additional carbon sequestration. In the case of a combination with BECCS, the BECCS alone case would be outcompeted. The BECCS case is inferior to the wood burial case due to limitations to technical capture rates of the BECCS process. If fossil fuels would be used in the BECCS process the slope would be flatter. The wood burial case almost follows the extrapolated growth of the young plantation. However, not perfectly as direct or indirect fossil emissions might be associated with the wood burial process. Wood burial could also stand for storage of submerged trees in sweet water where wood does not decay. For completeness we have added a DACCSs line which symbolizes the small land footprint of this technology, which, however, is very energy intensive (see Box 1 on p. 86). For the DACCS, fossil-free energy supply is assumed. Note that the figure does not include context-specific constraints, such as available capacities for CO_2 storage and wood burial.

The main take-away from Figure 1 is that, in terms of durable carbon sequestration, ecosystem management in combination with novel CDR methods outperforms carbon sequestration strategies that are purely based on NbS. The biological insight here is that with age NbS become less productive due to senescence and natural die-back of older trees and subsequent decay of biomass (heterotrophic respiration). Forest management through rejuvenation avoids senescence and novel CDR methods, such as HWP, biochar, and BECCS avoid decay of biomass and the associated re-emission of CO_2 into the atmosphere. Therefore, by necessity and first principles these technology combinations will eventually turn out to be superior to NbS only.

Figure 2 clarifies this relationship further. Here we define a carbon payback period between two novel CDR alternatives. The opportunity benefit of letting the plantation grow is benchmarked against the case where a plantation is cut according to a specific rotation period and the harvested wood is converted in a BECCS plant. What we can observe is that from a carbon accounting point of view its beneficial to let the forest grow since BECCS is a technology that cannot be implemented with 100% carbon capture efficiency. These CO_2 emissions that are associated with BECCS can only be compensated over time with an additional harvest/BECCS cycle while the plantation loses its net carbon sequestration productivity.

For illustrative purposes: If harvest occurs at half time to maturity of a forest (e.g., 10 years in a Eucalyptus plantation, 50 years in spruce) and BECCS efficiency is 75% then the payback period is 2.5 rotation periods (25 years in Eucalyptus and 125 years in spruce). After the payback period is exceeded the opportunity benefits of BECCS start to steadily increase as overmature forest become susceptible to decay. Note that not all natural ecosystems decline in their natural carbon stock. However, the slope of net sequestration will always be much smaller compared to the biomass based novel CDR case such as BECCS or biochar.

This simple example makes it rather clear that in areas of high productivity fast growing species combined with novel CDR methods will be the most competitive negative emission implementation strategies. In climate zones that are less productive NbS are likely to dominate as payback periods will be prohibitive both in physical accounting terms as well as economically.

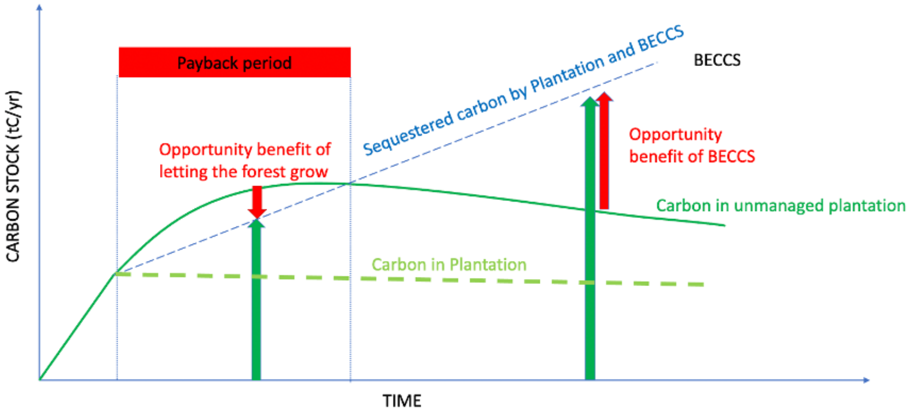

Figure 2: Graphical representation of carbon opportunity benefit and carbon payback period when comparing carbon sequestration results from unmanaged plantations and managed plantations in optional combination with BECCS as an illustrative example.

3.5 Technological approaches to managing impermanence of Nature-based Solutions

NbS, such as reforestation, afforestation, and wetland restoration, have a long history to be used as strategies to sequester carbon. However, the stability and permanence of the stored carbon remain a subject of concern, especially regarding the risk of carbon reversal. Non-permanence, or carbon reversal, refers to the risk that the carbon sequestered by NbS can be released back into the atmosphere, negating the mitigation efforts. This release of carbon can be a consequence of natural disturbances, human activities, or shifts in ecosystem health.

The most prominent reason for carbon reversal that is cited relates to natural disturbances. Events like wildfires, pests, diseases, and extreme weather conditions can destroy or degrade the ecosystems that store carbon. For example, a forest that has been capturing carbon for decades can release a significant portion of it if burned in a wildfire. However, there are also human activities that can cause carbon reversal. Deforestation, land-use changes, or poor management practices can reduce the carbon storage capacity of ecosystems or directly release sequestered carbon. The permanence of NbS is intrinsically tied to the communities living within or around these ecosystems. Without clear land tenure and rights, or without the inclusion of local communities in the decision-making process, NbS projects can face opposition or fail to be maintained in the long term.

Conversely, it is widely believed that NbS approaches respecting indigenous and local knowledge and prioritizing community ownership often see better outcomes and longevity. Shifts in ecosystem resilience due to climate changes can alter an ecosystem's carbon balance. Some ecosystems might need to transition through ways of disturbances. Globally, there are already early warning signals that the natural sink strengths are declining (Fernández-Martínez, et al., 2023) which might have significant feedback on the use of CDRs as they will have to compensate for the loss of anticipated carbon absorption by the biosphere. The risk of reversal of NbS could pose significant challenges for the operationalisation of Article 6 of the Paris Agreement.

Figure 3 provides an illustration of permanence risk management using novel CDR methods utilising biomass. The basic insight from this figure is that the forest carbon stock that is vulnerable to carbon reversal gets substituted by a more permanent form of storage when entering the engineered part of the technology cascade. When we take BECCS as the illustrative example showcasing this optional transition from a vulnerable to a more permanent form of storage. BECCS involves growing biomass, which sequesters CO_2 from the atmosphere during its growth as a forest. At this stage the build-up carbon store in the forest is considered vulnerable to disturbances. When this biomass is used for energy production (e.g., burned), resulting CO_2 is captured at the point of emission and stored underground in geological formations (or through mineralization) in a more permanent form. This makes the entire process not only net carbon negative, but also storage more permanent. However, the long-term integrity of these storage sites is crucial. If these storage sites were to leak, it would reintroduce the captured carbon into the atmosphere, thus increasing the carbon reversal risk again, but this time with probabilities shared with fossil fuel CCS sites. Proper site selection, monitoring, and maintenance are necessary for all of the novel forms of carbon storage such a biochar and HWP.

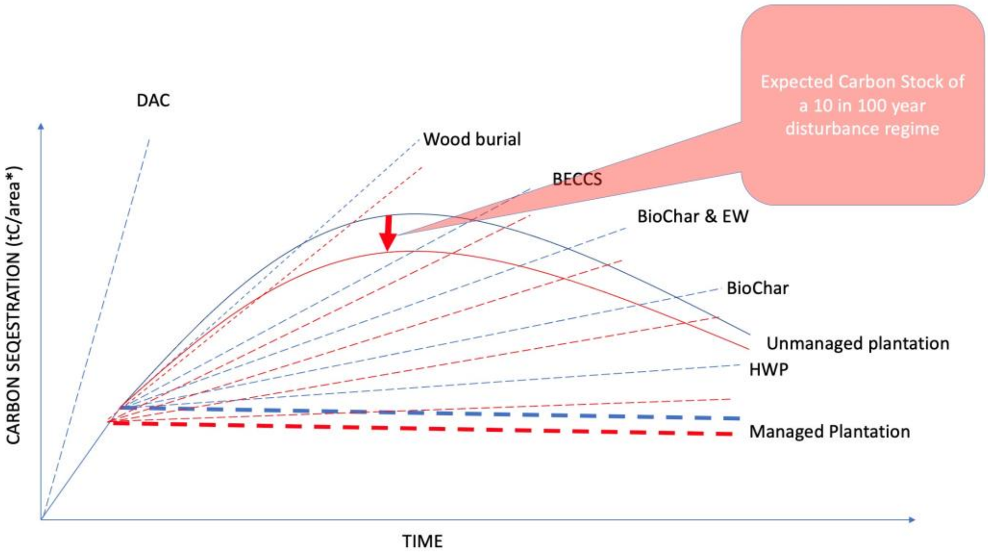

Figure 3: Illustrative example of carbon sequestration of different CDR methods over time under a disturbance regime. We have plotted in blue the same sequestration pattern as in Figure 1 and overlayed an estimate of an approximately 10 in 100 return period of a disturbance taking out most of the biomass sequestered up to that point. Here the assumption is that an expectation is taken over a large area of plantations. If we were to consider a small area, we would see a zigzag pattern marking individual disturbance events. Here we also assume that smaller amounts of wood that were subject to the disturbance (e.g., fire) could not enter the wood utilization pool. It has to be noted that under many disturbances (e.g., biotic or windthrow) most of the wood would still enter full wood utilization suggesting that the dashed red lines would all be more or less parallel.

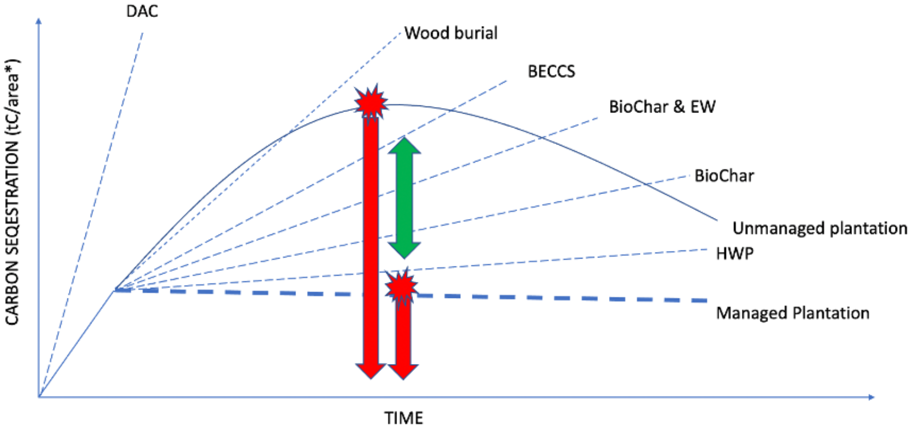

Figure 4: Impact of a single large disturbance event on natural and engineered carbon sequestration pools stemming from managed and unmanaged plantations/forests.

When looking at a single forest management unit which is under threat of a disturbance, Figure 4 suggests a disadvantage of the NbS strategy due to the relative higher vulnerability of the accumulated natural carbon stocks (RED) compared to the engineered carbon stocks (GREEN). What follows from this consideration are two strategic management incentives.

First, management of ecosystems under the hazard of a disturbances, which are at the same time subject to a carbon liability, will be managed for shorter term rotations and be combined with engineered CDR solutions. For example, the state of Austria is currently changing its forest law to reduce the minimum rotation period for managed forests due to increased hazards from bark beetle attack. If forest owners were directly liable for the associated carbon emissions, they would consider retrofitting for increased production of charcoal in many bioenergy plants to increase climate mitigation benefits apart from fossil fuel substitution from bioenergy (mainly in heating). A reduction in rotation period has additional ecological and societal advantages related to the accelerated climate adaptation of mountain forests and its related ecosystem services. It is thought that more adapted tree species can be introduced earlier as the climate is changing faster than anticipated by forest managers.

Shorter rotations and strategic species change will thus deliver higher resilience, but also necessarily lead to increased wood supplies. If these increased wood supplies will not be met by new demands from novel CDR methods triggered by targeted policies a cascading risk scenario might materialize as follows: Wood supplies from disturbances will lead to a situation where forests will no longer be harvested leading to increased decay of biomass leading to large areas of net emission forests as well as even larger opportunity benefits of novel wood-based CDR methods. In addition, forest managers will not be able to plant more climate adapted tree species unless targeted support policies are implemented.

There is a rather small chance for most ecosystems that no-active forest adaptation will lead to superior auto-adaptation outcomes due to the unprecedented nature and magnitude of climate changes under overshoot. In addition, it can be expected that many of the existing forests during their transition to adapt to a new climate will be invaded by undesirable invasive species. If kept unmanaged invaded forests might no longer be able to deliver the same ecosystem services and lead to substantial biodiversity damages. It is currently not known how many of the 4-5 billion hectares of closed canopy forests will react to the disturbances associated with the expected climate changes and what the consequences will be to potentially proactively managed the vulnerable carbon pools.

Measures to manage the risk of carbon reversal from NbS are varied and are typically highly context and place specific. Natural disturbances will never be fully eliminated; however, pre-emptive avoidance measures could be implemented widely such as forest fire and pest management reducing substantially the hazard. The human related reversal risk mainly related to land-use changes could also be addressed through improved resource governance. Risk management options, such as buffering and insurance mechanisms accounting for the risk of non-permanence are described in chapter 9.

4 Carbon dioxide removal under the Paris Agreement

This chapter provides an overview of the international carbon market instruments under Article 6, the global stocktake and the MWP, three areas of implementation of the Paris Agreement that are well placed to address carbon removal.

4.1 International carbon markets under Article 6

Article 6 is the carbon markets clause of the Paris Agreement and is designed to help raise climate ambition. It sets the basis for countries to cooperate to meet their climate targets by allowing emission reductions and carbon removals in one country to be traded and counted towards the target of another.

There are two ways for this cooperation to happen: firstly, through decentralised forms, such as bilateral cooperation in carbon crediting programmes and linkages between various national trading systems (Article 6.2), and, secondly, through a centralised UN-run mechanism (Article 6.4).

Article 6 covers emission reductions and removals[4] generated from 2021 onwards and is technology-neutral in its approach. The scope of carbon removal under Article 6 is not limited to certain specific CDR methods, although countries can decide to limit their activities. For example, Switzerland excludes biologic removals from their collaboration under Article 6 (Michaelowa, et al., 2023), and the Swedish Article 6 programme prioritises the mitigation of energy-related emissions and has currently no intention to engage in land use-related removals (Swedish Ministry of Environment, 2022; Sveriges Radio, 2023).

The use of removals under Article 6.2 depends on what the countries bilaterally agree upon or on the coverage of their linked emission trading systems. Article 6.2 is already operational, but countries are so far focusing their collaboration on emission reductions,

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[4] SBSTA is currently negotiating the inclusion of emission avoidance and conservation enhancement activities to the scope of Article 6.4 mechanism. As of October 2023, these emission avoidance activities are not in the scope of Article 6.4. Emission avoidance in this context refers narrowly to reducing emissions from deforestation and forest degradation (REDD+ projects), not to be confused with how the term “emission avoidance” is used in the voluntary carbon markets where some stakeholders use it as a blanket term for emission reductions and avoidance.

with bilateral agreements already in place between 30 host countries and 6 buyer countries.[5]

Article 6.4 of the Paris Agreement establishes the Article 6.4 mechanism, a carbon crediting instrument that countries can voluntarily use to trade credits from emission reduction and removal projects. The mechanism is not yet operational and is governed by the Supervisory Body[6] (SB) that is responsible for establishing guidance and procedures, approving methodologies, registering projects and issuing credits, among many other tasks.

In November 2023, The SB finalised preparing the foundation for how the Article 6.4 mechanism will apply to removals ("recommendation on activities involving removals") (UNFCCC, 2023). The SB received over 300 stakeholder submissions[7] on removals since it was established in 2022 and has used this input over extended deliberations to prepare its recommendation.[8] If the upcoming CMA5 during COP28 adopts the SB recommendations on methodologies[9] and removals, the Article 6.4 mechanism will finally become operational.

Specific requirements for removals under Article 6.4 include "appropriate monitoring, reporting, accounting for removals and crediting periods, addressing reversals, avoidance of leakage, and avoidance of other negative environmental and social impacts" (UNFCCC, 2021). These are particularly relevant for land-based biological activities due to the complexity of their socio-economic-environmental dimensions and their significant spatial needs (Michaelowa, et al., 2023).

There is a growing ecosystem of novel CDR methods. Many of these are poised to be used by countries in achieving their climate targets as the Nationally Determined Contributions (NDCs) are updated, and the understanding of the role of removals and national capacity to deploy them develops.

So far, the discussions in the Article 6.4 SB have been the main forum of CDR-related deliberations under the Paris Agreement. Given the lack of broadly accepted international accounting rules for a range of removal methods, the decisions taken

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[5] https://www.ieta.org/resources/visualising-article-6-implementation/
[6] https://unfccc.int/process-and-meetings/bodies/constituted-bodies/article-64-supervisory-body
[7] https://unfccc.int/sites/default/files/resource/a64-sb007-aa-a13.pdf
[8] https://unfccc.int/sites/default/files/resource/a64-sb007_a07.pdf
[9] https://unfccc.int/sites/default/files/resource/a64-sb009-a01.pdf

under Article 6.4, and the methodologies approved under it, are bound to have an outsized impact on carbon markets globally.[10]

International carbon markets are increasingly converging with the voluntary carbon markets, although a complete conversion is unlikely given that not all jurisdictions will use international carbon markets. Historically, the Clean Development Mechanism (CDM) was created as a compliance market under the Kyoto Protocol, but CDM credits (CER) have primarily been used in VCM over the last decade. In the opposite development, the compliance market for international aviation, CORSIA, recognises a long list of VCM programs in their list of Eligible Emissions Units.[11] South Africa and Colombia allow the use of VCM credits for the national carbon tax.

When it comes to Article 6, some countries are relying on VCM infrastructure in Article 6.2 arrangements[12], Article 6.4 methodologies are bound to learn from the best practices of the VCM, and some of these will likely be submitted for approval under Article 6.4, and some countries will let corporates use Article 6 credits under VCM. Hence, most likely it will not be straightforward to distinguish the role of the international carbon markets, compliance markets in general, or voluntary carbon markets when considering the role of markets and removals. Eventually, the carbon markets may shape into a matrix where the carbon credit supply from independent crediting standards and supply directly through Article 6 are interlinked with voluntary demand (corporates' use to meet their voluntary climate targets) and compliance demand.[13]

4.2 Global Stocktake

The global stocktake is a process for countries and stakeholders to see where they're collectively making progress towards meeting the goals of the Paris Agreement – and where they're not. It's a two-year process that takes place every five years, with the first-ever stocktake concluding at COP28 in 2023.

The stocktake has three parts: information collection and preparation, technical assessment, and consideration of outputs.[14] The first two have been finalised, and

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[10] "Governance expansion" and policy diffusion across different baseline-and credit systems was evident in the Kyoto Protocol era and has accelerated since the adoption of the Paris Agreement, and the public governance expansion is likely to continue if the Paris Agreement is perceived to be successful in safeguarding integrity (Ahonen, Kessler, Michaelowa, Espelage, & Hoch, 2022).

[11] https://www.icao.int/environmental-protection/corsia/pages/corsia-emissions-units.aspx

[12] https://www.greenbiz.com/article/article-6-creates-two-kinds-carbon-credits-what-means-business

[13] https://evetamme.com/2023/11/09/converging-vcm-and-compliance-markets/

[14] https://unfccc.int/topics/global-stocktake/components-of-the-global-stocktake

the work is ongoing on the outputs that will be referenced in a CMA decision in November 2023 and/or declaration.

A global stocktake synthesis report published in October 2023 includes several references to carbon removal (UNFCCC, 2023a). It highlights the three complementary roles of carbon removal (see section 3.1), indicates that the scale and support for carbon removal methods are not consistent with what is needed, and calls on operating entities of the UNFCCC Financial Mechanism[15] to deliver on mandates, including by supporting carbon removal technologies (CCU/S and DAC) in line with the Green Climate Fund's governing instrument.

Therefore, the global stocktake process is an opportunity to highlight the role of carbon removal, the need to align financial flows to scale up carbon removal methods, and the need for a more detailed representation of carbon removal in NDCs in the upcoming CMA decision.

4.3 Mitigation Work Programme

All elements of the Paris Agreement that focus on mitigation are relevant for carbon removal because climate change mitigation, as a term, by default, includes both emission reductions and carbon removal (UNFCCC, 2023b).

The Mitigation Work Programme (MWP) was established at COP26 to "urgently scale up mitigation ambition and implementation in this critical decade" to help reach the temperature goal of the Paris Agreement. It operates between 2023-2026 (and can be continued after 2026) with a primary goal of encouraging countries to align their targets and actions towards net-zero in a manner that complements the Global Stocktake.

The first MWP Global Dialogue covered a wide range of topics, some relevant to carbon removal.[16] Carbon removal and negative emissions feature in the 1st Report on the first global dialogue (UNFCCC, 2023b) but only in the context of carbon capture, storage, and utilisation. The broader context of the role of the whole carbon removal ecosystem has not been captured by the MWP so far.

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[15] https://unfccc.int/funds-and-financial-entities

[16] https://unfccc.int/event/first-global-dialogue-and-investment-focused-event-under-the-sharm-el-sheikh-mitigation-ambition-and

Given the progress to date, the temporary nature and the divergent views among countries on how the MWP should operate, it is less likely to provide meaningful guidance on carbon removals compared to the global stocktake and Article 6.4. That can change if countries are interested in using the MWP to, for example, send market and/or policy signals, and develop guidance or benchmarks for sectors. In the case of carbon removals, it could be selected as a topic for the MWP to focus on in the Global dialogues and Investment-focused events, where countries could establish guidance to help countries align their targets and actions. Guidance to provide more details on removals in updated NDCs would be one of the useful examples.

5 Review of literature addressing opportunities and limitations of carbon markets for the incentivisation of carbon dioxide removal

Historically, carbon removal has played a limited role in international carbon markets apart from A/R (Michaelowa, et al., 2023). The available literature is somewhat limited and fragmented across CDR methods, making it difficult to draw conclusions on the role of markets in scaling carbon removals, and vice versa.

When using markets, the magnitude, value, and patterns of mitigation transactions in reaching a global net-zero target are dynamic and depend on several factors, such as how widely CDR is deployed and the timing of reaching net-zero in different regions (Yu, et al., 2021). According to Edmonds et al., (2019), Article 6 has the potential to reduce the total cost of implementing NDCs by more than half (~$250 billion/ year in 2030) or, alternatively, facilitate the removal of 50 per cent more emissions (~5 $GtCO_2$ per year in 2030), at no additional cost. The paper does not provide information about the respective roles of emission reductions and carbon removals in the trading. Yu et al. (2021) find that the land-use emissions in 2030 change from -2.9 $GtCO_2$ per year without using markets to -5.3 $GtCO_2$ per year when using markets. Meanwhile, the role of conventional land-based removals gradually declines over time, and novel carbon removal methods become increasingly important (Ibid).

5.1 Carbon markets can address uneven distribution of carbon removal potential

Article 6 will become an especially necessary tool when the NDCs approach net-zero emissions. Since countries have different capacities for net-negative emissions and varying amounts of residual emissions, trading under Article 6 will likely be necessary to incentivize countries with excess capacity to go net-negative to balance out remaining emissions from countries without the ability to mitigate to net-zero (Edmonds, Forrister, Clarke, de Clara, & Munnings, 2019). For example, not all regions are equally endowed in sustainable biomass and CO_2 storage (Fajardy & Mac Dowell, 2020). The geographic dispersion of carbon removal capacity implies that many countries without meaningful carbon removal options will depend on other countries to offset their residual emissions (Iyer et al., 2021). Thus, carbon credit trading constitutes important value creation opportunities for key providers of CO_2 removal (Fajardy & Mac Dowell, 2020).

Hence, the right market conditions can help to scale carbon removals. Article 6.2 is seen as a potential entry point for bilateral or plurilateral carbon removal piloting activities that would allow for pre-testing elements of the market instruments and provide a proof of concept of such cooperation (Zetterberg, Johnsson, & Möllersten, 2021). At the same time, Mohan et al. (2021) find that given the cumbersome UNFCCC negotiations on the implementation of Article 6, it seems premature to assume that international market mechanisms would allow developed countries to meet their fair share of carbon removal by setting up projects in developing countries, as the predecessor under the Kyoto Protocol failed to meet sufficient environmental integrity standards.

5.2 Carbon removal addresses equity in climate targets

The inclusion of carbon removal in the Paris Agreement's Article 6 market mechanisms is seen as a tool for addressing equity in the large-scale carbon removal deployment foreseen to meet the Paris Agreement temperature goal (Lee, Fyson, & Schleussner, 2021). Carbon removal in Article 6 could accelerate technology transfer and provide a source of international finance for carbon removal deployment in countries with less responsibility or capability while at the same time incentivising more ambitious carbon removal contributions from major emitters (Olsen, et al., 2021).

5.3 Financing carbon removal with Article 6

Price levels under Article 6.4 are expected to remain insufficient for many CDR methods due to significant upfront capital and near-term operating expenses for novel CDR methods (Honegger & Reiner, 2017) (Poralla et al., 2021). The majority of currently operational mechanisms in carbon markets mainly support cheaper conventional NbS-based CDR methods (Hickey et al., 2023). To address this barrier, progressive countries could offer a premium on top of market prices that would account for the elevated cost levels of technologies which have not yet made their way down the cost curves (Poralla et al., 2021). Or, the other way around – the availability of international carbon markets could be used to harness the cost differentials that result from different national policies leading to different subsidy rates per tonne of carbon removal (Honegger, et al., 2022).

If increased demand for emission reduction credits resulted in a market price that enables high-durability CDR methods to compete, carbon removal deployment could be accelerated as a natural component of mitigation (Honegger & Reiner, 2018). For BECCS, this could happen when the market price reaches \$100–\$150/t CO_2, possibly around 2030. For DACCS, it would probably take much longer (Honegger & Reiner, 2018).

5.4 The role of conventional nature-based and novel CDR methods

Several authors state concerns regarding the scope of CDR methods to be covered under Article 6 and question the environmental integrity of including land-use related activities in its scope. Risks around additionality, baselines and leakage vary considerably among different types of land-use activities, and including these under the Paris Agreement raises questions about whether and how these risks can be appropriately addressed (Böttcher, Schneider, Urrutia, Siemons, & Fallasch, 2022; Hickey, Fankhauser, Smith, & Allen, 2023; Lee, Fyson, & Schleussner, 2021).

If carbon removal can accurately be measured, reported, and verified, is additional, permanent and does not cause carbon leakage – Article 6 could provide a longer-term accounting system for novel removals developed in other countries (Kachi, Warnecke, & Höhne, 2019).

As explained in section 3.4, the forest reaches a point of saturation as it grows and matures. At maturity, forests can no longer provide net carbon uptake (Yu, et al., 2021).

Olsen et. al. (2021) exclude biological CDR options like A/R from their analysis completely because these methods are widely acknowledged to be unsuited for inclusion in the Article 6 market mechanisms, given their monitoring and accounting challenges, among other reasons.

Some authors argue that emissions should be offset with like-for-like carbon removal, with CO_2 from fossil fuel sources balanced with low-risk storage. The likely outcome with conventional NbS-based CDR methods is shorter-term carbon storage, which makes it best suited to addressing land-use emissions or short-lived GHG (Hickey, Fankhauser, Smith, & Allen, 2023).

CDR has the inbuilt advantage that most novel CDR methods can clearly show their "additionality" to business-as-usual, which has been difficult for emission reduction technologies that usually generate revenues from the sale of goods or services. This makes the case for the operationalisation of carbon removal under Article 6 (Honegger, et al., 2022).

5.5 Emission reductions and carbon dioxide removal – separate targets, separate markets

Several authors suggest separate targets for emissions reduction and CDR (Pozo, Galan-Martin, Reiner, Mac Dowell, & Guillén-Gosálbez, 2020; Honegger, et al., 2022). Olsen et al. (2021) argue that international transfer based on carbon removal mitigation outcomes transfers should not obscure urgent domestic emission reduction efforts by big emitters causing mitigation deterrence (see section 7.6 for an explanation). Therefore, a market for novel CDR methods that is managed separately from the market for emission reductions is proposed as a way forward that allows responsible incentivising of CDR deployment and investment through carbon markets. Where separate carbon removal targets are established, markets are still needed as inter-regional trading is required to meet CO_2 removal targets at the least cost (Fajardy & Mac Dowell, 2020).

Michaelowa et al. (2023) note that carbon credit prices of CDR methods under the VCM range between single USD levels for A/R credits and several thousand USD for DACCS.[17] The authors propose that compliance market regulators may design different classes of carbon removal markets to also accommodate more expensive and more permanent solutions, although they see a challenge in generating demand for these expensive classes.

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[17] However, high price niches are very small and their growth path remains uncertain.

5.6 Carbon markets will transition towards carbon removal markets

As global emissions approach zero on the way to net negative emissions, international market-based cooperation under Article 6 will, over time, increasingly shift focus from emissions reduction activities and have a new and different role in carbon removals (Honegger, Poralla, Michaelowa, & Ahonen, 2021; Hickey, Fankhauser, Smith, & Allen, 2023; Olsen, et al., 2021). However, this requires a shift from offsetting continued emissions to rapidly avoiding and reducing all emissions possible and going further to draw carbon out of the atmosphere (Kachi, Warnecke, & Höhne, 2019).

6 Literature-based cost comparison

6.1 Principles for comparing emission reductions and carbon removal

Comparing reducing emissions versus removing carbon from the atmosphere is a complex task with many important considerations beyond simply cost. While in theory, very few emission sources are physically impossible to eliminate, certain sectors or activities may be very "hard to abate" - meaning the costs or other negative impacts of phasing them out completely could be prohibitive. When deciding whether to utilize CDR methods instead of further emissions reductions, several key factors should be weighed for both emission reductions and CDR. The scope of this assignment emphasizes cost. While this chapter and Chapter 7 focus on abatement costs and economic optimization, a broader and more holistic discussion concerning factors impacting investment decisions and the development of carbon removal capacities is presented in section 7.7.

6.1.1 Cost of emission reductions

The IPCC's Sixth Assessment Report (AR6) estimates costs and potential of different emission reduction measures (mitigation options) until 2030 (IPCC, 2022). Potentials for different cost levels are provided, showing that some mitigation options rise in cost as they are deployed. Table 2 summarizes the estimated cost across potentials.

Table 2: Average cost per tonne of CO_2 avoided (USD/tCO_2e) and potentials for emission reduction mitigation options. Source: IPCC (2022).

Type of effort	Average cost per tCO_2e avoided (USD)	Potential 2030 – cost low-end of range (Gt)	Potential 2030 – cost high-end of range (Gt)
Avoid demand for energy services	0	2,1	5,6
Efficient lighting, appliances and equipment	0	2	7
Fuel efficient light duty vehicles	0	0,44	1,32
Shift to public transportation	0	0,43	1,29
Shift to bikes and e-bikes	0	0,16	0,48
Fuel-efficient heavy duty vehicles	0	0,37	1,11
Shipping-efficiency and optimization	0	0,27	0,81
Aviation- energy efficiency	0	0,15	0,45
Wind energy	9	0,21	0,68
Energy efficiency	10	0,67	1,61
Reduction of non-CO_2 emissions	10	1,4	5,5
Reduce CH4 emission from coal mining	13	0,3	1,3
Solar energy	16	2,53	7,35
Reduce emission of fluorinated gas	20	1,2	4,9
Reduce CH4 emission from oil and gas	24	0,6	2,8
Reduce CH4 emission from solid waste	29	0,1	0,9
Material efficiency	35	1,0	2,7
Enhanced recycling	35	0,28	0,84
Cementitious material substitution	35	0,54	0,91
Reduce conversion of natural ecosystems	37	0,88	1,77
Reduce CH4 and N2O emission in agriculture	39	0,35	0,70
Hydropower	40	0,20	0,34
Geothermal energy	40	0,3	0,5
Biofuels	40	0,56	0,56
Nuclear energy	54	0,30	0,89
Fuel switching (electr., nat. gas, bioenergy, H2)	56	0,27	0,80
Carbon sequestration in agriculture	57	0,10	0,29
Improvement of existing building stock	67	0,18	0,54
Forest management, fire management	68	0,11	0,32
Feedstock decarbonisation, process change	75	0,36	0,67
Restoration, afforestation, reforestation	81	0,12	0,32
Onsite renewable production and use	103	0,35	1,05
Carbon capture and storage	113	0,86	1,43
Bioelectricity	113	0,70	1,16
New buildings with high energy performance	117	1,57	2,62

Reduce CH4 emission from wastewater	120	0,29	0,48
Carbon capture with utilization and storage	150	0,11	0,36
Enhanced use of wood products	NA	0,21	0,35
Reduce food loss and food waste	No cost estimated	0,15	0,25
Shift to sustainable healthy diets	No cost estimated	0,7	1,5
Electric light-duty vehicles	No cost estimated	0,54	0,68
Electric heavy-duty vehicles	No cost estimated	0,09	0,27

Adapted from the IPCC AR6 Figure SPM 7 See their methods and considerations here:
https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/

These cost estimations from the IPCC AR6 are based on net lifetime costs of avoided greenhouse gas emissions, compared to a reference technology, collated from about 175 sources. The mitigation potentials for each option are assessed separately and may not be cumulative.

The IPCC AR6 also looks at the marginal abatement cost of reaching climate targets, estimating the marginal costs for the fractions of emissions to be abated. For limiting global warming to 2°C, marginal abatement costs are estimated to be around $90 per ton of CO_2 in 2030 and $210 per ton in 2050. These figures escalate to $220 and $630 per ton in 2030 and 2050, respectively, for 1.5°C pathways.

Goldman Sachs' latest Carbonomics Marginal Abatement Cost (MAC) curve from 2022 indicates that 10% of global GHG emission reductions have negative costs, 50% of total emission reductions cost less than 100 USD per tonne CO_2, 70% less than 200 USD/t and 10% currently being "unabatable" without cost estimates. The highest costs come from transportation with most reductions exceeding 700 USD/t (Goldman Sachs, 2022). The cost estimates are currently experiencing a rapid year-on-year decline, for example, the 2019 Carbonomics estimates only 60% of GHG reductions were estimated to cost less than 200 USD/t.

In a U.S.-specific context, the Environmental Defense Fund estimates that spending $0-60 per ton will achieve 48% of the required reduction towards net-zero emissions, whereas a cost range of $90-150 per ton will cover 77% of the reductions, leaving 23% that will require over $150 per ton to mitigate (EDF, 2021).

It is worth noting that these are GHG estimates using GWP 100 calculations, which obscure what part is CO_2 emissions and what part is other gasses. This has relevance for what carbon removal to compare with. As described in chapter 7 of this report, the like-for-like removal principle suggests that N_2O emissions (which are especially hard to abate) can be compensated with medium-term lived storage such as forestation. Methane, to the degree it needs to be, could be compensated with cheaper short-term storage. (Scenarios that halt warming are not dependent on net GHG net-zero. The global carbon budget for 1.5C assume that about half of today's methane emissions continue indefinitely for example.)

6.1.2 Cost of carbon dioxide removal

To determine the most up-to-date future cost estimates for carbon removal we performed a literature review, looking at over 40 different studies from 2017-2023, with 75 different cost estimates.[18] For the summary table, we then grouped the different approaches within each method, taking the average low and high cost across all the different estimates for each method. (Note that this summarization hides details and nuance. For example, combining all DAC technology estimates into one hide that some are expected to be cheaper than others.)

Most estimates we found were for 2050, or for 'nth of a kind' describing a scenario where the method is scaled up to megatonnes or more. For some methods, there is a need for more R&D to bring down costs, others are more dependent on economies of scale without the need for additional technological breakthroughs. Cost estimates can be hard to compare. Some estimates rely on very optimistic cost of energy and capital for example. Some methods, such as forestation, are expected to become more expensive with deployment as the most suitable land is used first.

We also looked at the current cost of the CDR methods, using data from the market data platform cdr.fyi. Today's prices reflect the high cost of doing essentially prototype carbon removal. All novel CDR methods are expected to fall in cost.

Table 3 shows the summarized future cost estimates from our literature review, together with prices from cdr.fyi. We also contrast that to the cost estimates from the IPCCs AR6, finding that in most cases estimates match reasonably well, with our range being narrower in some cases. Finally, we show the estimated 2050 potential of each method as reported in the AR6.

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[18] See https://docs.google.com/spreadsheets/d/18FMT0MXcYNUJ41KsIGUmZ7hP_rJ6D-9ujPUg_xo0pRg/edit#gid=1878212870.

Table 3: Cost of CDR methods (USD/$tCO_{2removed}$). Source: our literature review (see sources in appendix, cdr.fyi, and IPCC AR6.

All costs in USD		Cost our literature review		Reported current prices (cdr.fyi price data Jan 2019-Sep 2023)				IPCC AR6 cost estimate		IPCC AR6 estimate of potential/yr 2050	
CDR method	Approach	Average low cost	Average high cost	Lowest price reported	Highest price reported	Mean price	Weighted average price	Costs (lower bound)	Costs (upper bound)	Low	High
BECCS	Overall	57	145	300	300	300		15	400	0.5	11.0
Biochar	Overall	53	163	97	600	176	193	10	345	0.3	6.6
Biomass terrestrial storage	Biomass terrestrial burial			44	601	257	111				
Biooil	Biooil injection			300	660	580	506				
DAC	Overall	133	585	321	2 345	1 120	718	100	300	5.0	40.0
ERW	Overall	51	196	75	1 577	392	332	50	200	2.0	4.0
Forest	Afforestation & Reforestation	10	50					0	240	0.5	10.0
mCDR	Macroalgae	33	133	220	269	248	245				

mCDR	Artificial Upwelling and Downwelling	100	150								
mCDR	Coastal Blue Carbon	10	50					40	260	0.0	1.0
mCDR	Electrochemical	192	299	984	1 953	1 505					
mCDR	Ocean alkalinity enhancement (minerals)	46	141					40	260	1.0	100
mCDR	Ocean Fertilization	66	158					50	500	1.0	3.0
Soil	Soil Carbon	0	83					-45	100	0.6	9.3
Storage	Saline Aquifer	7	13								
Storage	In-Situ	9	20								
Storage	Sequestration in On-Land Basalt and Peridotite Rocks	10	30								
Storage	Sequestration in Subsea Basalt Rocks	200	400								

6.2 Conclusion

As the cost estimates of removals and reductions show, the vast majority of emission reductions are cheaper than carbon removal through novel CDR methods. But, in the emission reduction analysis above 23% (US) /30% (Global) of emission reductions cost over 150/200 USD or are not possible to abate with current technology. This puts them at the range of cost estimates for carbon removal. And the marginal abatement costs for 1.5C are well over the costs for CDR methods. Especially sustainable fuels such as biofuels and synthetic e-fuels have very high cost estimates and could be candidates for using carbon removal.

7 Contrasting emission reductions and carbon removal in illustrative mitigation scenarios

7.1 Model overview

Our study comprises four illustrative global climate mitigation pathways using a bespoke reduced complexity model that is calibrated on the latest climate mitigation scenario literature from the integrated assessment community. The model essentially builds upon and refines the one presented in Bednar et al. (2021). Each of these scenarios is an ensemble formed by 7 different parameter sets within the model. Figure 5 presents the resultant “scenario envelopes”, showcasing minimum, maximum, mean, and median projections of carbon emissions and removals of one illustrative scenario ensemble. Derived from the ENGAGE scenario intercomparison (Riahi, et al., 2021), our model calibration employs data from seven out of nine detailed process-based integrated assessment models (dp-IAMs), hence, each parameter set of our model reflects the properties of one dp-IAM. We found data consistency issues in the two IAMs that were excluded from this assessment. We call these ensembles “scenarios” and their individual parameter-specific scenarios as “variants” of an ensemble. All scenarios align with the SSP2 “middle of the road” socio-economic narrative.

Mitigation efforts are classified either as emissions reductions or as carbon removals (see Figure 6). Emission reductions are typically computed against a set baseline, making them baseline-dependent, whereas carbon removals are baseline-independent, as standard baseline assumptions usually do not account for removals. In Figure 6, and subsequent figures, “Sequestration” refers to geological CO_2 storage, encompassing various forms of Carbon Capture and Storage (CCS), including BECCS and DACCS. Hence, Sequestration includes both emission reductions (e.g., fossil CCS) and carbon removals, but excludes sinks within AFOLU accounting or generally called NbS.

Sectoral breakdown in the model

In the modelling framework, three primary sectors contribute to carbon emission reductions and removals: Energy; Agriculture, Forestry, and Other Land Use (AFOLU); and Industry, in that order of importance for carbon emissions. All sectors are presented as global aggregates and are then downscaled for regional analysis.

The **Energy Sector** incorporates primary energy from biomass, non-biomass renewables, and nuclear. The primary mechanism to mitigate emissions is the substitution of fossil fuel-based energy production with renewable zero-carbon sources. There is also a provision for a reduction in final energy demand as a mitigation strategy. “Unconventional mitigation methods” are also recognized, especially CCS. When paired with bioenergy, it results in BECCS. While BECCS is considered a removal, CCS in conjunction with fossil fuels is classified as an emission reduction. It is noteworthy that the CCS aspect of bioenergy is typically more effective than bioenergy's direct emission reductions, owing to biomass's relatively lower conversion efficiency for both liquid fuels and electricity generation when compared to fossil fuels. Another removal technology associated with the energy sector is DACCS. Its representation is limited in the IAM literature as currently only 2 of the 7 models explicitly include DACCS. For DACCS, its energy consumption is inherently high: due to fundamental physics, the energy required to remove CO_2 from the atmosphere using DACCS exceeds the initial energy from the fossil fuels that resulted in the CO_2 emissions. Thus, the use of DACCS induces a substantial additional demand for energy and can only deliver carbon negative outcomes if the energy system is sufficiently decarbonized (See also Box 1).

The **Industry Sector** integrates both industrial process emission reductions and CCS, both classified as emission reductions. Note, this does not include direct industrial energy use, which is covered by the Energy Sector.

Lastly, the **AFOLU Sector** in the model is unique in its reporting. Only net emission figures, i.e., the sum of gross emissions and removals, are provided in the published scenario databases. For the sake of clarity and simplicity, outputs from the AFOLU sector are generally grouped as removals. Another distinctive feature of the AFOLU sector is its reduced sensitivity to carbon price signals, a design choice made by the IAMs to curb potential negative land use change repercussions from high carbon prices in dp-IAMs. Typically, IAMs exclude the behaviour of the natural sink of unmanaged ecosystems (Nabuurs, Ciais, Grassi, Houghton, & Sohngen, 2023).

Scenarios operate under a global carbon price. A second price path can be instituted for distinct technologies, mirroring targeted mitigation policies.

Here we present the narratives of our four global mitigation scenarios. A comparative lens is employed to gauge their efficiency concerning global climate objectives as well as "mitigation and decarbonization deterrence". Following this approach, we dissect quantities, potentials, costs, and timing facets of emission reductions and carbon removal within these scenarios. We then present a regional perspective, spotlighting the origins of carbon removals, regional demand variations, and how burden sharing alters these dynamics.

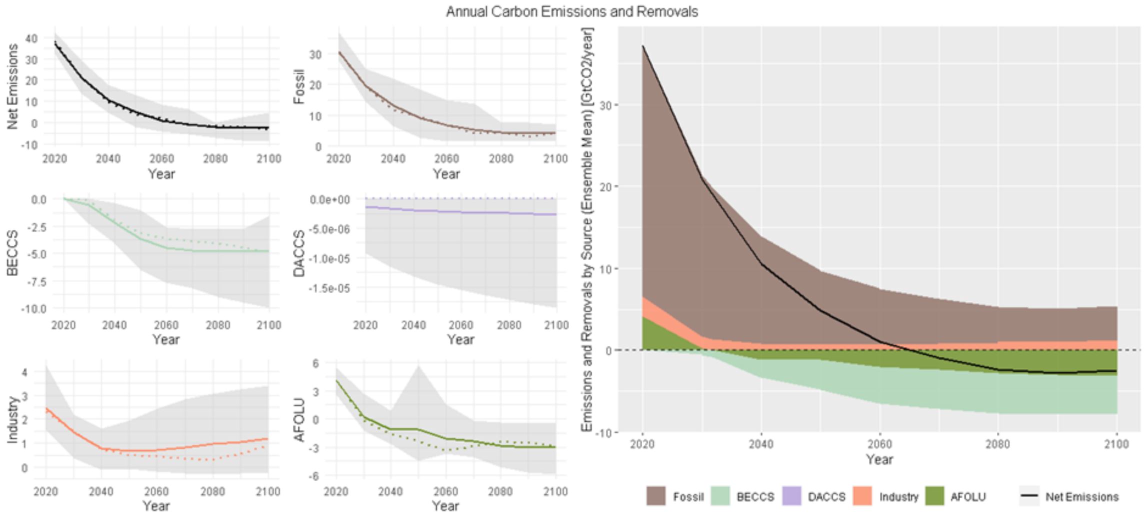

Figure 5: Carbon emissions and removal in an illustrative scenario ensemble, labelled "Proactive Transition" (GtCO$_2$/yr). Small panels left-hand-side: "Scenario envelopes", characterized by min to max ranges, as well as mean (solid line) and median paths (dotted line). Large panel right-hand-side: Mean paths of CO$_2$ emissions and removals of the scenario ensemble. Note industry and fossil energy emissions are net of any CCS.

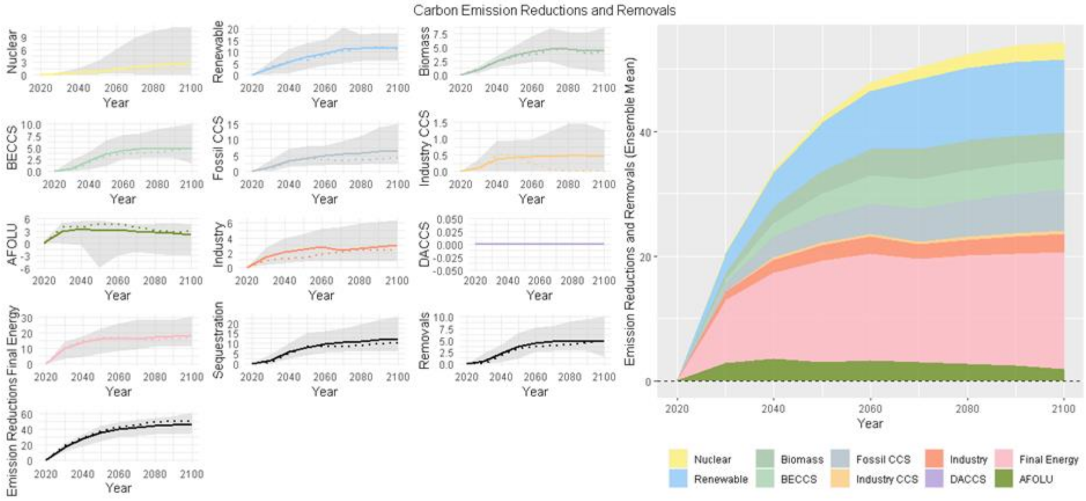

Figure 6: Carbon emission reductions and removal (GtCO2/yr) of same illustrative scenario ensemble as in Figure 5. Small panels left-hand-side: "Scenario envelopes", characterized by min to max range, as well as mean (solid line) and median paths (dotted line). Large panel right-hand-side: Mean paths of CO2 emission reductions and carbon removals in scenario ensemble.

7.2 Narratives for four scenario ensembles

Here, we present the narratives of four illustrative mitigation scenario ensembles, as shown in Figure 7 and Figure 8.

1. Proactive Transition

In this scenario ensemble, decarbonization relies heavily on primary energy substitutes, including biomass, nuclear, and non-biomass renewables, with a clear goal: the swift displacement of fossil fuels. Parallel to this, policies aiming to cut back on final energy consumption are assumed to deliver tangible results. From the outset, the roles of CCS and carbon removal are firmly recognized to minimize near-term overshoots. This understanding prompts the deployment of substantial amounts of both CCS and carbon removal. As time progresses, however, the incentives for CCS and carbon removal gradually diminish. Due to the strong early push, CCS and its associated infrastructure seamlessly integrates with bioenergy generation (resulting in BECCS), fossil fuel processes, and various hard to abate industrial applications. Broad-scale adoption of DACCS is challenged. Carbon pricing and other policy tools are designed to draw a distinction between emission reductions, and the tandem of carbon removal and CCS. This scenario ensemble creates the least climate overshoot.

2. Gradual Realization

In this scenario ensemble, carbon policy leverages traditional mitigation strategies from the onset. Their push for replacing fossil fuels with alternatives like biomass, nuclear, and non-biomass renewables is just as ambitious as in the Proactive Transition scenario. However, the distinct difference lies in the approach to carbon removal and CCS. For much of the early phase, incentives or carbon pricing mechanisms are almost exclusively targeted at emission reductions. The profound potential and necessity of carbon removal and CCS become evident to policymakers only as we near 2050. The realization triggers a pronounced shift towards integrating both carbon removal and CCS to address global temperature stabilization and any temperature overshoots that may occur. This scenario ensemble creates a noticeable climate overshoot.

3. Unified Market Approach

In this scenario, the emphasis is on an integrated market system, where a single price covers both carbon removal and emission reductions. The emergence of an integrated market facilitates the trade of "removal units" (Macinante & Singh Ghaleigh, 2022) on par with emission reduction certificates. Notably, the inclusion of DACCS introduces additional energy demand. It is imperative to note that this approach is recognized as the most cost-effective pathway, but it is not devoid of challenges. One major concern is "decarbonization deterrence," where near-term emphasis on emission reductions might be overshadowed by carbon removal further in the future for cost reasons. The emissions caused by delayed decarbonisation and their subsequent end-of-century removal cause a substantial overshoot.

4. Delayed Decarbonization

The Delayed Decarbonization scenario sees a deferral in decarbonization efforts by a decade, resulting in a more pronounced temperature overshoot. As a response to this delay, there is a heightened and intensified focus on carbon removal, which incorporates a larger role for DACCS. While the decarbonization strategies employed are reflective of those in the Gradual Realization scenario, the emphasis on carbon removal is distinctly more amplified, aiming to counterbalance the ramifications of the earlier delay.

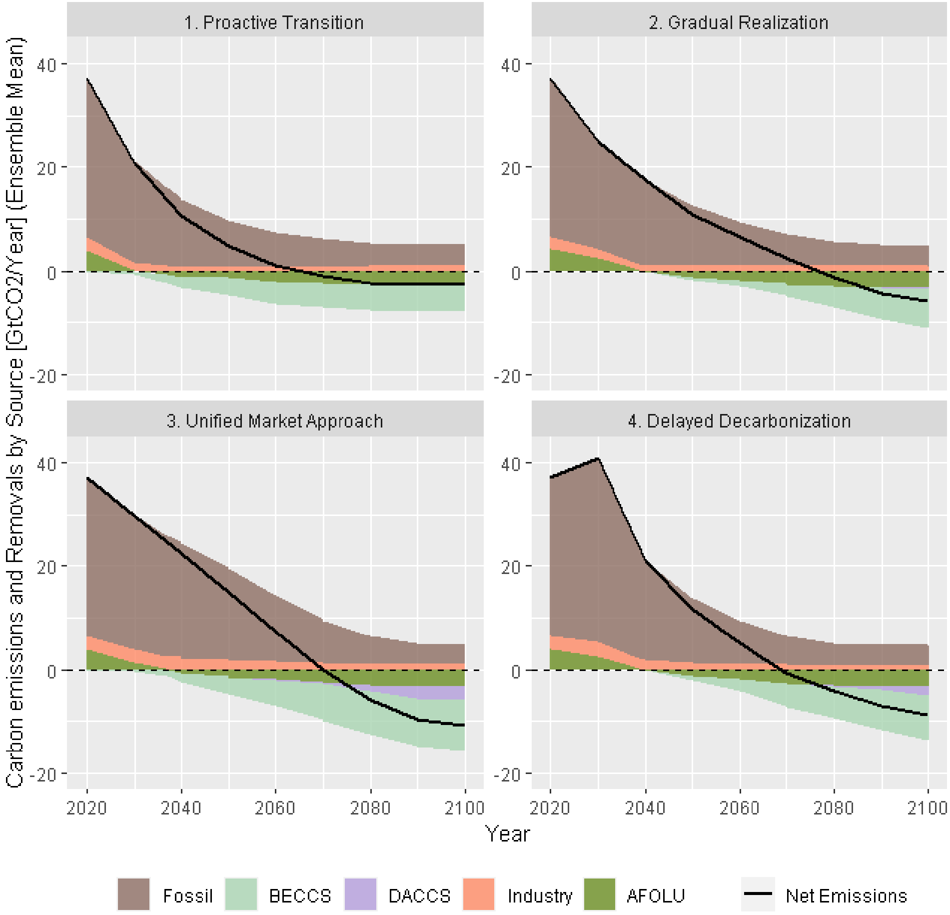

Figure 7: Four illustrative climate mitigation scenarios. Ensemble means of CO_2 emissions and carbon removals. Fossil and industry CO_2 emissions are net of CCS.

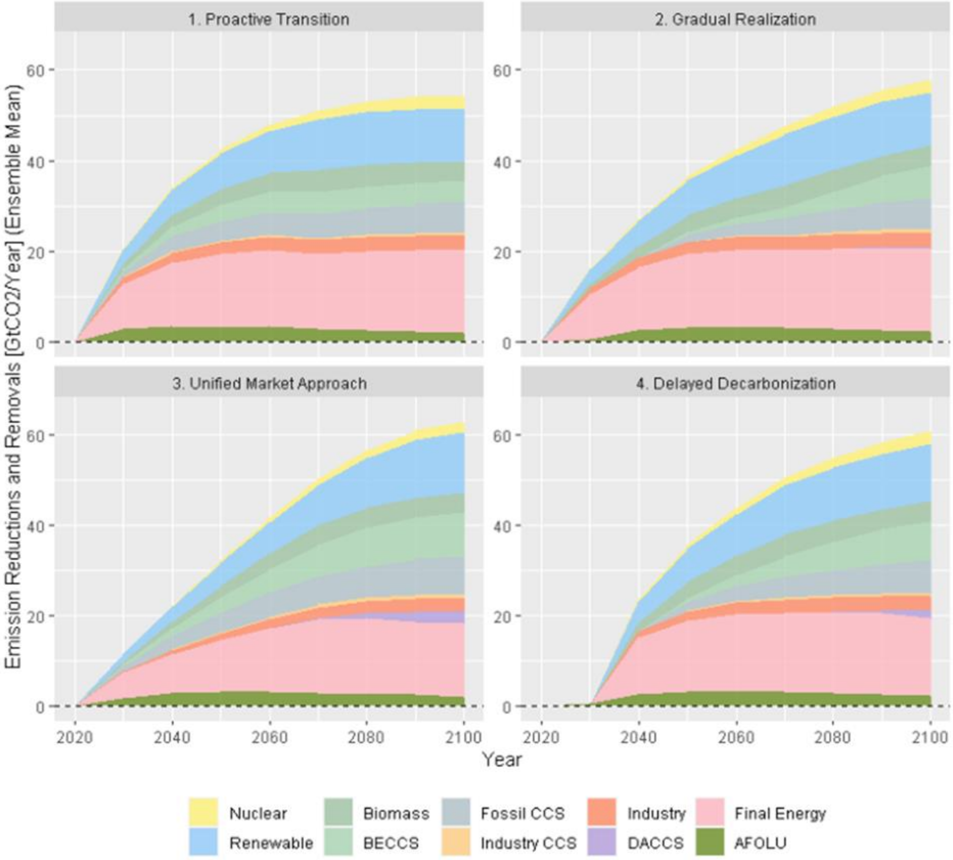

Figure 8: Four illustrative climate mitigation scenarios. Ensemble means of CO_2 emission reductions and carbon removals.

7.3 Global scenario analysis

7.3.1 Shared traits across all scenarios

Every single one of the four scenarios calls for unparalleled efforts. Notably, in each case, emission reductions are more dominant than carbon removals, as detailed in Figure 9. When considering the importance of strategies in terms of reducing emissions or removing atmospheric CO_2, there is a discernible order: First, curtailing final energy demand; second, the adoption of renewables. Next in line are fossil CCS and BECCS, and finally, there is deployment of bioenergy. Emission reductions and Sequestration are larger in the 2060-2100 period than in the 2020-2060 period. Sequestration is larger than removals because it entails fossil energy CCS and industrial CCS. Removals occur in the AFOLU sector.

Figure 9: Cumulative carbon emission reductions, carbon removals, and sequestration in the first and second half of this century. Sequestration entails CCS from various sources, including fossil energy and industrial process CCS, BECCS and DACCS. Sequestration points to permanent CO_2 storage in geological formations. Removal here refers to sinks in the AFOLU sector such as afforestation and reforestation.

7.3.2 Scenario analysis in the context of global climate goals

Analysing Figure 7 and Figure 8, it becomes clear that even when decarbonization (i.e., emission reductions) is pursued aggressively (as exemplified in Scenarios 1 and 2), reaching global net-zero CO_2 emissions within the envisioned timeline mandates a swift and significant integration of both CCS and carbon removal. In fact, it is important to note that without the tandem of CCS and carbon removal, achieving net-zero CO_2 emissions is unattainable across all proposed scenarios.

Turning to Figure 10, it is evident that, in the long term, all scenarios gravitate towards a temperature rise ranging from 1.5 to 1.7°C, as showcased in panel 2 of Figure 10. Scenario 1 stands out for its enhanced potential to meet ambitious targets, primarily since it avoids a pronounced temperature overshoot. Cumulative CO_2 emissions in Scenarios 3 and 4 from 2020-2060 (visible in panel 1) exceed those from 2020-2100 (in panel 2). This differential underscores the emissions overshoot that then necessitates reversal upon achieving net-zero CO_2 emissions.

However, such overshoots carry inherent risks:

- Reliance on current CDR methods might be misguided, given uncertainties about their scalability in the future.

- The political endorsement of carbon removal could waver, either due to unforeseen side effects or mounting financial and fiscal constraints. For instance, net carbon removal, which is essentially net negative emissions after achieving net-zero, present a challenge. Without mechanisms in place to charge today's emitters for future carbon removal, these costs will inevitably be borne by public budgets, effectively using tax money to finance net carbon removals. The financial burden could be well above 2% of global GDP (Bednar, Obersteiner, & Wagner, 2019) – and this excludes the costs of CDR for compensation of residual emissions, the costs of emissions reductions or any expenditures targeting adaptation or loss and damage. Hence, another problem is the potential diversion of funds. As the tangible impacts of climate change take hold, resources earmarked for mitigation may be repurposed towards addressing loss and damage or facilitating adaptation.
- Overshoot periods amplify climate risks, especially as they might catalyse tipping points. Notably, the overshoot phase could be marked by heightened climate-induced damages and additional emissions from declining ecosystems.

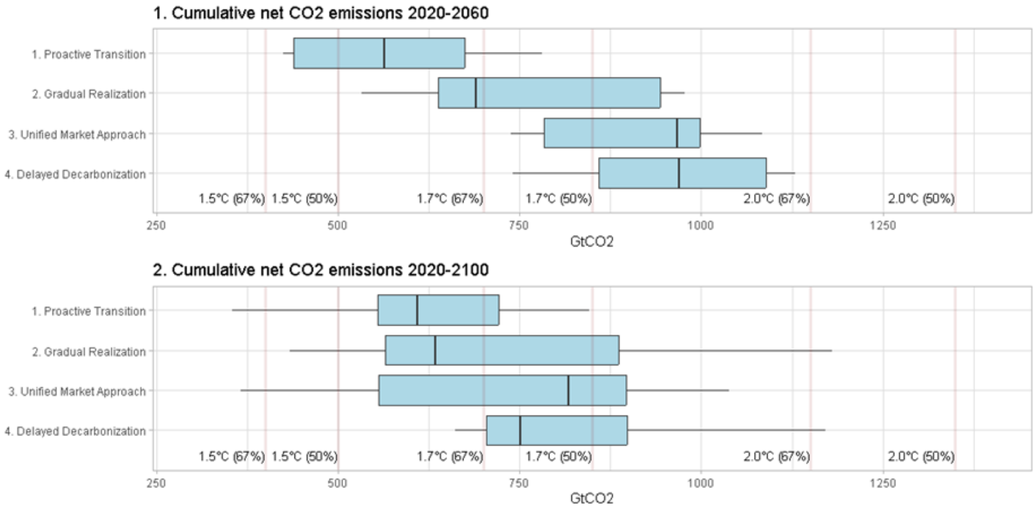

Figure 10: Cumulative net CO_2 emissions from 2020-2060 (panel 1) and 2020-2100 (panel 2) from all scenarios illustrated as box-and-whiskers plot. Remaining carbon budgets for limiting warming to 1.5, 1.7 and 2°C given a likelihood of 50% and 67% for the 2020-2100 period are indicated as vertical lines (Canadell, et al., 2021).

7.3.3 Quantities, potentials, timing, costs

To enhance the analysis, various aspects of carbon emission reductions and removals across distinct time periods are visualized:

- Figure 11 presents the total emission reductions and carbon removals, broken down by type and period (2020-2060 and 2060-2100).

- Figure 12 showcases the maximum annual potential for emission reductions and carbon removals. It also pinpoints the year when 20% of the full potential is reached.
- Lastly, Figure 13 details the average costs associated with each type of emission reduction and carbon removal by period.

In the context of these figures, each scenario offers a unique perspective:

Scenario 1 – Proactive Transition: Emphasizes high carbon removals and emission reductions in the near-term (see Figure 11), leading to correspondingly elevated costs during this period for both carbon removals and emission reductions. Collectively, this renders it the least cost-effective scenario in total system discounted cost terms under standard dp-IAM assumptions, that is, a 5% market rate of interest.

Scenario 2 – Gradual Realization: Mirrors Scenario 1 in terms of the rapid emission reductions brought underway, but with a noticeable near-term reduction in CCS and removals from 2020 to 2060. Despite a slight uptick in the 2060-2100 period, there is a limitation in achieving much higher carbon removal and CCS quantities due to restricted ramp-up speeds. This lag results in escalated costs for carbon removals and CCS in the 2060-2100 window, largely attributed to missed cost reduction through technological learning.

Scenario 3 – Unified Market Approach: This economically efficient scenario leverages the gains from discounting future mitigation costs. Scenario 3 specifically capitalizes on this by deferring a more significant portion of its emission reductions quantities and associated costs to the 2060-2100 period. As a result, even though this timeframe sees heightened costs relative to other scenarios, in total their present-day valuation implies a cost advantage of Scenario 3. This approach offloads a greater financial responsibility onto future generations. Moreover, it prolongs the year for reaching 20% of the full potential across most emission reductions, leaving a considerable share of near-term decarbonization potential untouched. Note that removals in the 2020-2060 period are as crucial as in scenario 1 for two key reasons: firstly, achieving large-scale removals by 2060-2100 requires their timely ramp-up; and secondly, during the 2020-2060 period, removals often substitute for emission reductions when they prove more cost-effective than emission reductions.

Scenario 4 – Delayed Decarbonization: Features a delayed decarbonization trajectory, which inadvertently raises average costs once mitigation gets underway.

This surge is due to the heightened required efforts and the pressing need to tap into global mitigation potentials at a faster rate.

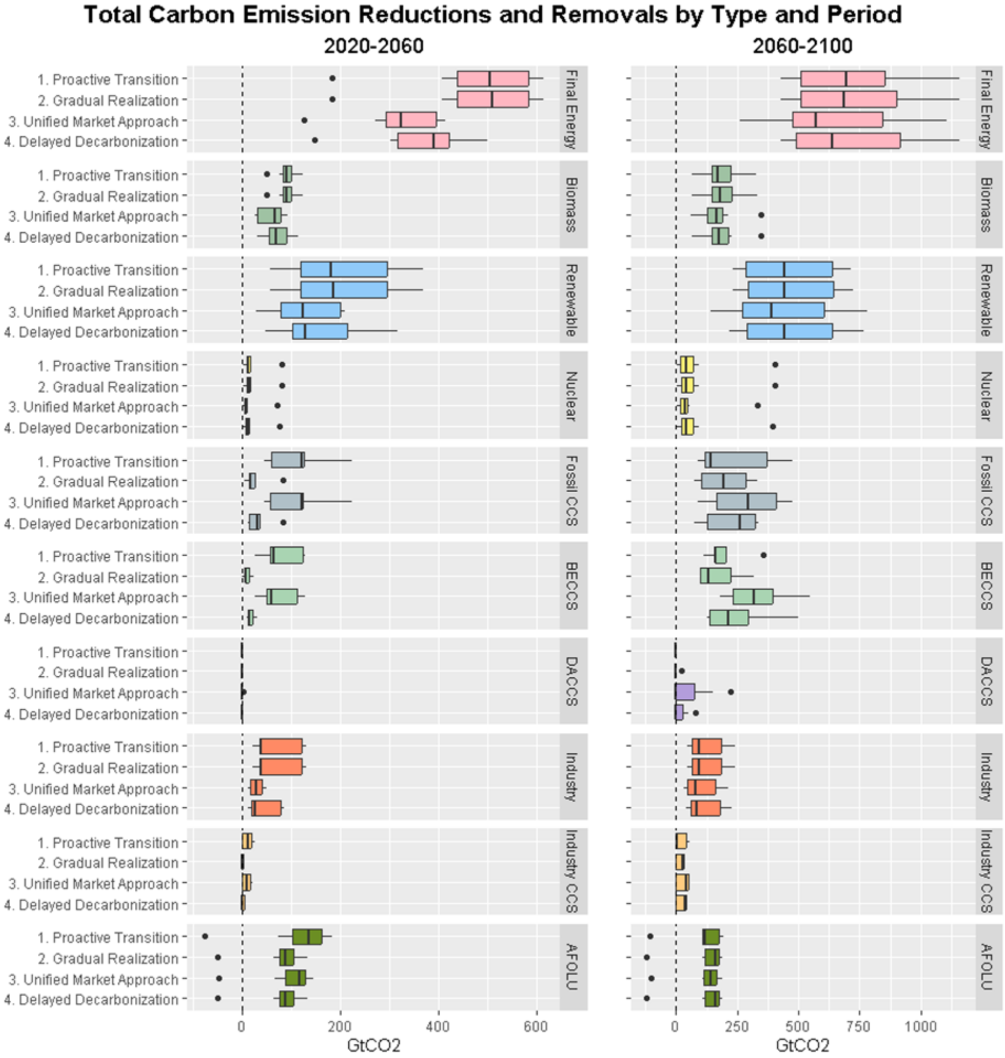

Figure 11: Cumulative carbon emission reductions and removals by scenario ensemble split into the periods 2020-2060 and 2060-2100.

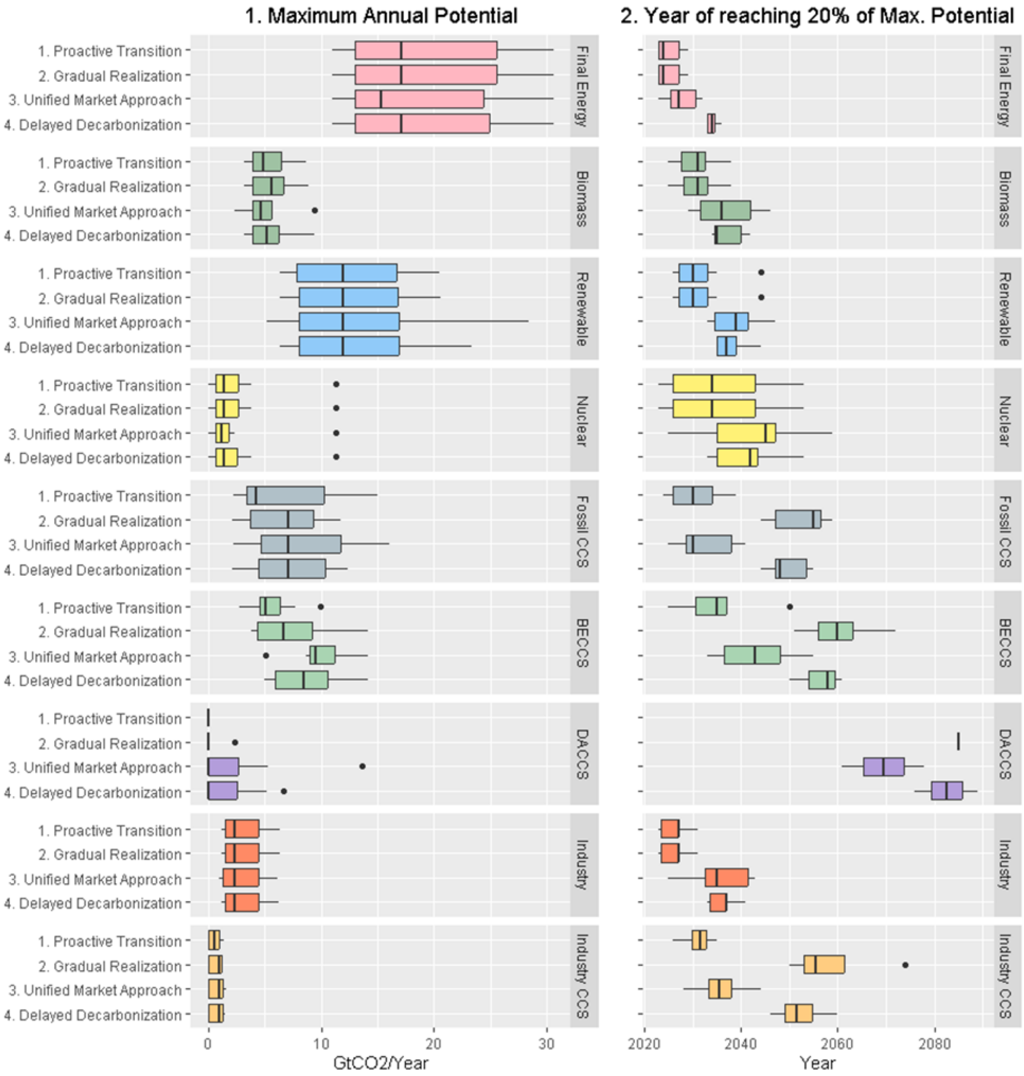

Figure 12: Maximum annual potential for carbon emission reductions and removals (panel 1) as well as the year at which 20% of this maximum potential is achieved (panel 2).

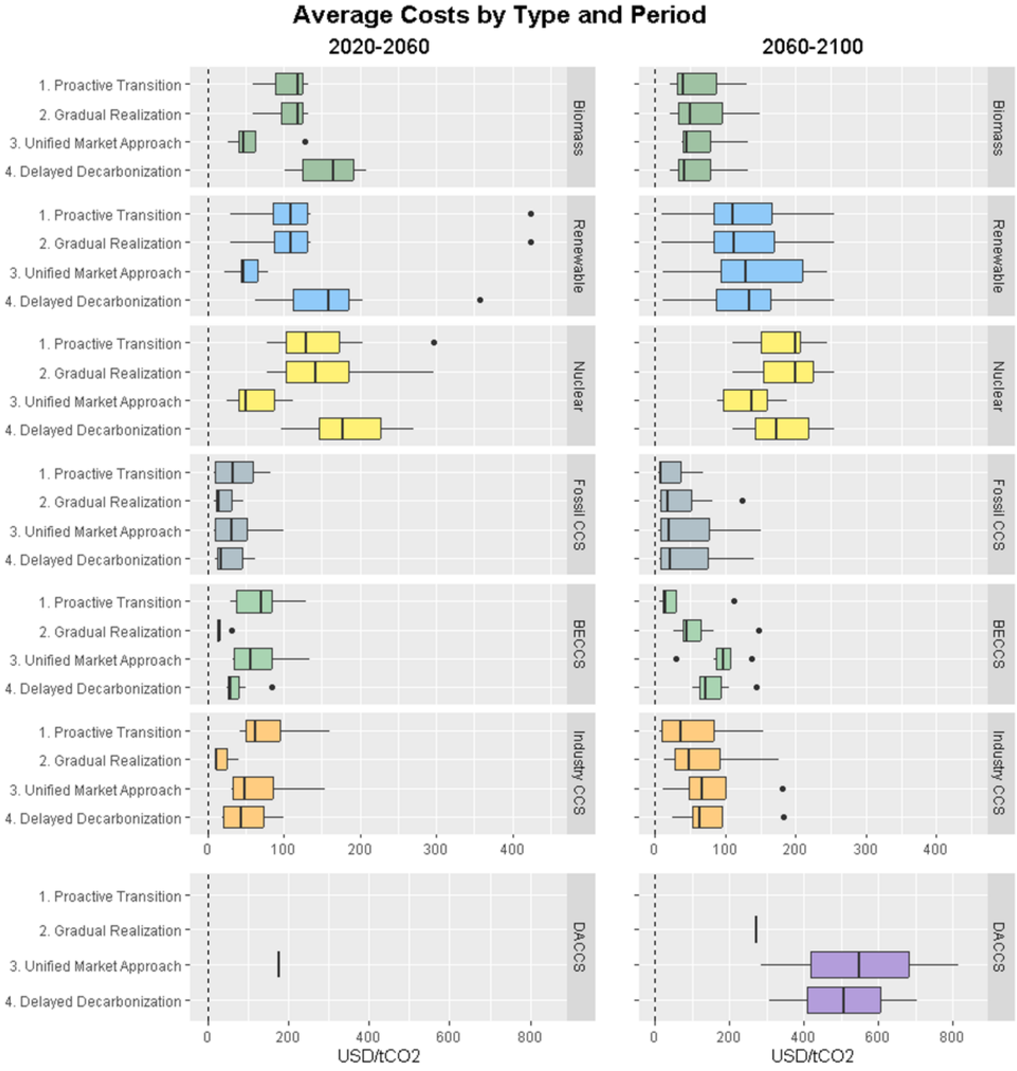

Figure 13: Average costs for carbon emission reductions and removals are presented for two periods: 2020-2060 and 2060-2100. It is important to observe the distinct cost scale assigned to DACCS. Out of the 7 variants within each scenario ensemble, only 2 incorporate DACCS. As a result, the boxplot represents the minimum-maximum range and its midpoint. If a boxplot is missing, it suggests that no variants deploy DACCS during that period. A solitary vertical line denotes the deployment of DACCS in just one of the variants of the ensemble for the specified period.

7.4 Regional scenario assessment

In our study, global scenarios are translated to a regional representation based on the IPCC's R10 region specifications. An inconsistency emerges when comparing the regional definitions in the AR6 technical annex[19] to those used in the AR6 scenario database. This discrepancy arises from the various definitions of regions in dp-IAMs

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[19] https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Annex-II.pdf.

which do not always overlap. Notably, there were inconsistencies observed for the categories “Rest of the World” and “Sub-Saharan Africa.” However, it is vital to highlight two aspects: firstly, key regions in terms of emissions align accurately, and secondly, our ensemble methodology ensures that any discrepancies become averaged out over the entire dataset.

The regional analysis consolidates global Scenarios 1-4 without distinction, presenting data ranges from the collective set. As the scaling methodology remains consistent across all scenarios, breaking down the results scenario-wise at a regional level would not only complicate the representation of findings but also would not yield any additional insights not already evident from the global analysis.

To offer a glimpse into potential regional emission trajectories, we reference Figure 14, which delineates emission profiles for our benchmark Scenario 1 across ten global regions, along with the “Rest of the World.” Certain trends can be immediately discerned: China is leaning more towards decarbonization methods inclusive of CCS rather than focusing on carbon removals. Latin America, while possessing robust decarbonization potential, is also indicating a preference for BECCS, afforestation, and reforestation, possibly to support other regional economies. Europe, North America, and Pacific OECD broadly adhere to the global trajectory. A more granular division of carbon removals, segmented by region and period, can be perused in Figure 15. For clarity, only the net AFOLU removals are taken into consideration for Figure 15; these correspond to values below zero in Figure 14 and not the entirety of reductions when compared to baseline values.

It is noteworthy that the deployment of DACCS is predominantly observed in energy-rich regions such as North America, the Middle East, and Russia. Given that DACCS does not feature across most scenario ensemble variants, its representation is chiefly through outliers within the box-and-whisker plots.

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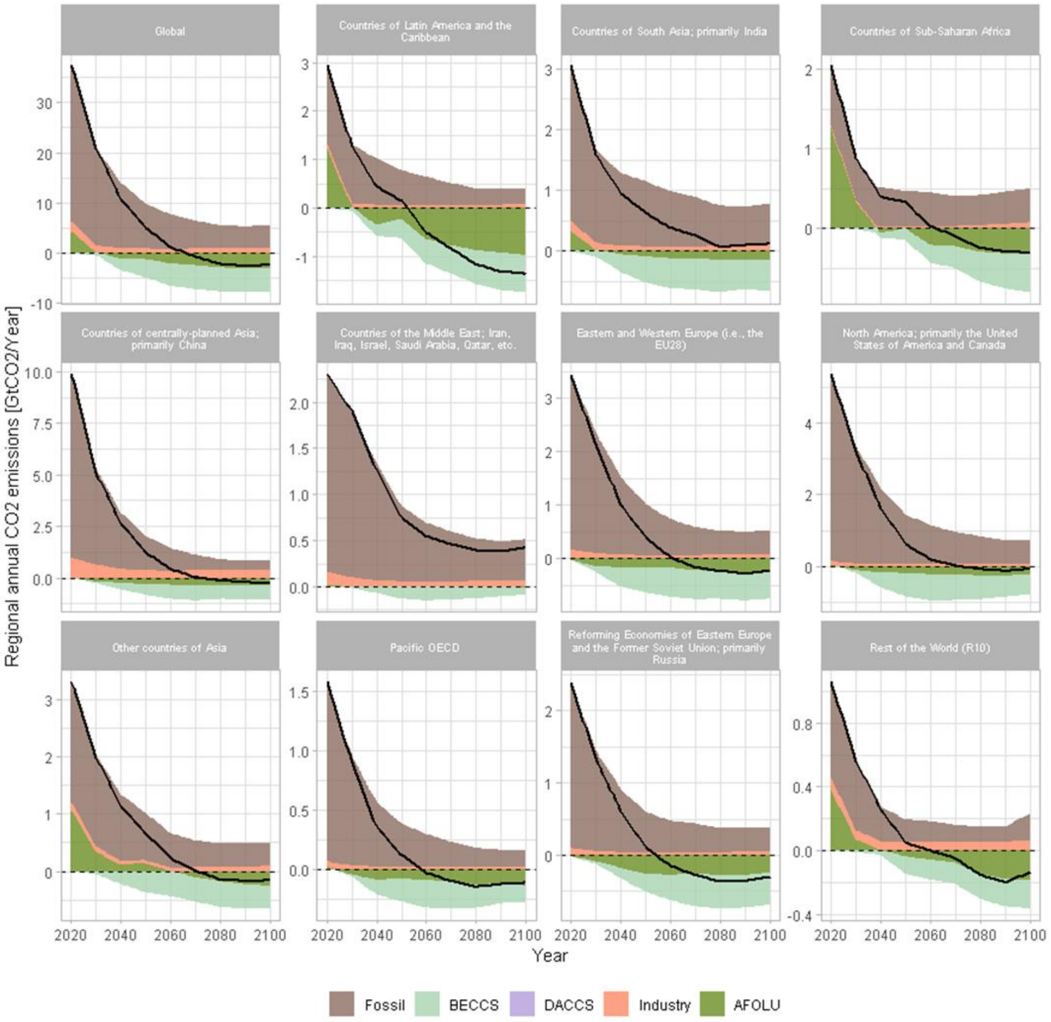

Figure 14: Regional carbon emissions and removals profiles of Scenario 1, Proactive Transition. The panels show ensemble means. Fossil and industry CO_2 emissions are net of CCS.

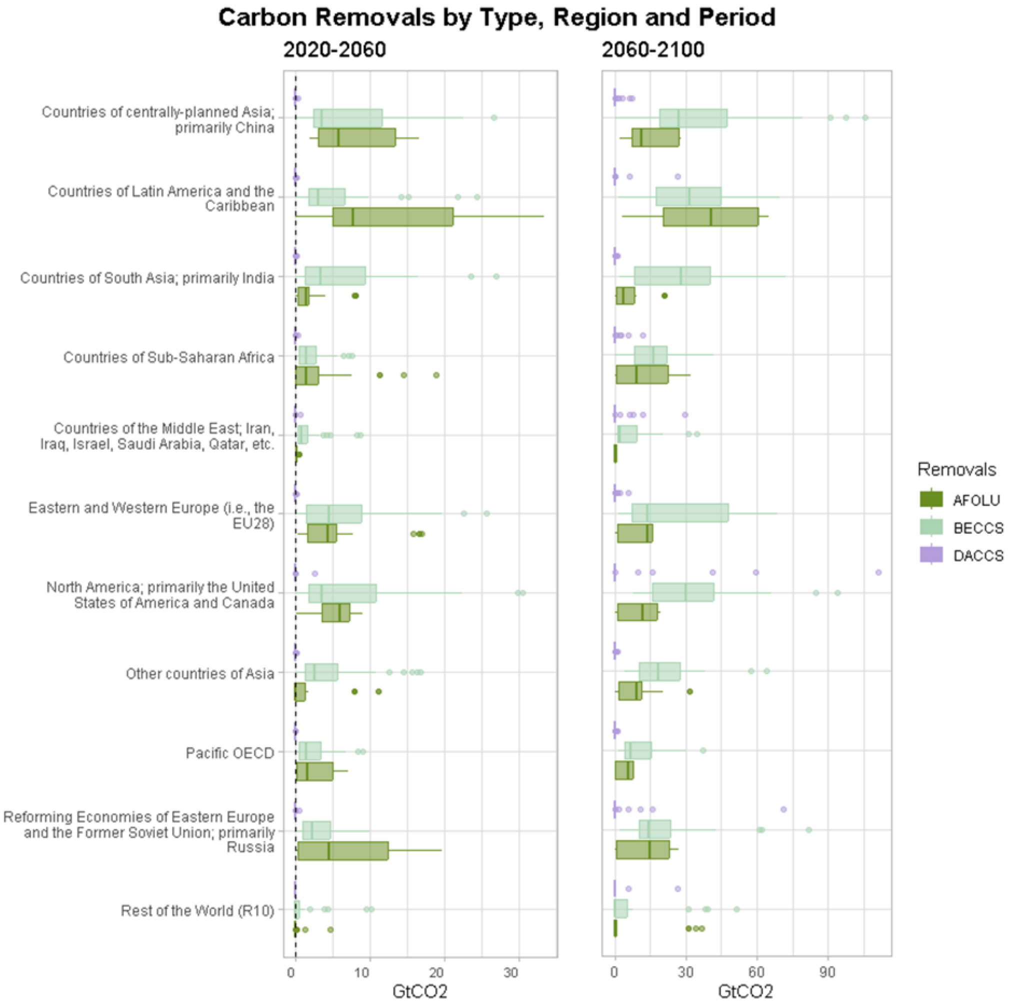

Figure 15: Carbon removals categorized by type and period across all regions. The AFOLU sector's carbon removals are represented as regional net removals, consistent with Figure 14. While the median values for DACCS are zero—due to its presence in only 2 out of the 7 scenario ensemble variants—the outliers in the box-and-whiskers plot signify DACCS potential in those specific variants.

7.5 Removals trade potential

This section seeks to answer two pivotal questions: Do regions function primarily as emitters or removers? And, based on this designation, which regions are poised to import removal units, and which can export additional removal units?

Figure 16 illustrates the extent to which regions contribute to global emissions and carbon removals across varied timescales. Whether a region stands as an exporter or importer of carbon removals is contingent upon their specific burden-sharing arrangements. Hence, a perceived imbalance in this figure does not directly infer the capability of regions to supply additional removals to the global market, or the need to import carbon removals. Nonetheless, the representation is instructive in discerning regions maintaining a relative balance between emissions and removals and those showcasing pronounced disparities. For clarity, it is crucial to understand the representation of cumulative values in the figure: 2060 encapsulates the 2020-2060 timeframe, while 2100 covers the 2020-2100 period, with 2020 depicting the actual values for that year. Notable disparities over the 2020-2100 period are seen with China and the Middle East (tilting more towards emissions than carbon removals), contrasted with Latin America and Reforming Economies of Eastern Europe (with a predominant lean towards removals over emissions). However, note that China gradually reduces its share of global emissions over time. This mirrors results of a previous study (World Bank, Ecofys, and Vivid Economics, 2016) where some regions, such as the Middle East, with insufficient sink capacity to offset residual emissions rely on importing carbon removals from among others Middle and Latin America and Africa.

The question of which regions will take on the roles of carbon removal exporters or importers is intricately tied to global burden-sharing protocols. To clarify this concept, Figure 17 and Figure 18 outline two distinct burden-sharing scenarios and the potential for resulting carbon trade. The underlying logic of these figures is explained as follows:

1. **Regional carbon budget allocation:** Each region is allocated a specific portion of the remaining global carbon budget according to a specified burden sharing arrangement. While following the same set of rules, note that the regional budgets are different for each scenario, and each variant within the scenario. The global budget corresponds to the (variant-specific) cumulative net emissions for specific time intervals, namely from 2020 to 2100, from 2020 to 2060, and from 2060 to 2100. The sum of the 2020-2060 and 2060-2100 budgets equals the 2020-2100 budget. Typically, the budget for 2020-2060 is larger than that for 2060-2100, and in certain scenarios, the 2060-2100 budget may even be negative.
2. **Distinguishing Mitigation Outcomes, emissions reductions and removals:** In this context, we differentiate between emissions reductions and removals supplied to the global market. "Mitigation outcomes" encompass both removals and emissions reductions, which can either be supplied to or demanded from the global market.
3. **Calculating supplied emission reductions and removals:** Supplied emission reductions represent the difference between the regional budget (as a fraction of the global budget, as defined by the burden-sharing arrangement) and the

regional cumulative gross emissions for each defined period. If a region's cumulative gross emissions are lower than its budget, it can sell the surplus on the market as emission reductions. However, if cumulative gross emissions exceed the regional budget (as is often the case), the surplus emissions must be subtracted from cumulative removals. The remaining removals can then be offered on the global market.

4. **Addressing shortfalls:** In cases where removals are insufficient to bridge the gap between cumulative gross emissions and the regional budget, the region must acquire additional mitigation outcomes from the market. It is worth noting that, for imports, there is no distinction made between emission reductions and removals. However, it is argued later in this report that distinguishing between these two categories can be beneficial for various reasons. This distinction would entail defining separate cumulative targets for gross emissions and gross removals.

Figure 17 adopts a “regressive” burden-sharing model where regions are granted a share of the remaining global carbon budget that mirrors their 2020 global emissions contributions. This approach naturally benefits high emitting economies, such as China, North America, and Europe. Values left of the zero line indicate a need for regions to import Mitigation Outcomes, while those to the right suggest potential for export. Intriguingly, over the 2020-2060 span, China emerges as an exporter, attributed to its significant initial allocation from the global carbon budget combined with marked emission reductions. However, extending this view to the 2060-2100 timeline reveals China transitioning into an importer role, indicating that any Mitigation Outcomes exported en route to net-zero might necessitate re-import subsequently.

In Figure 18, a progressive burden-sharing paradigm is presented. Here, regions are allotted shares of global emissions proportional to their global population shares. This framework, inherently favouring developing regions like South Asian countries (inclusive of India) and Sub-Saharan nations with modest per-capita carbon footprints, positions these regions as exporters. Such a distribution proves challenging for China and North America, especially considering projected significant population decline in China within this century. Europe’s position is moderately impacted under this structure, but when juxtaposed against the prior burden-sharing model, it aligns more with the less advantaged group.

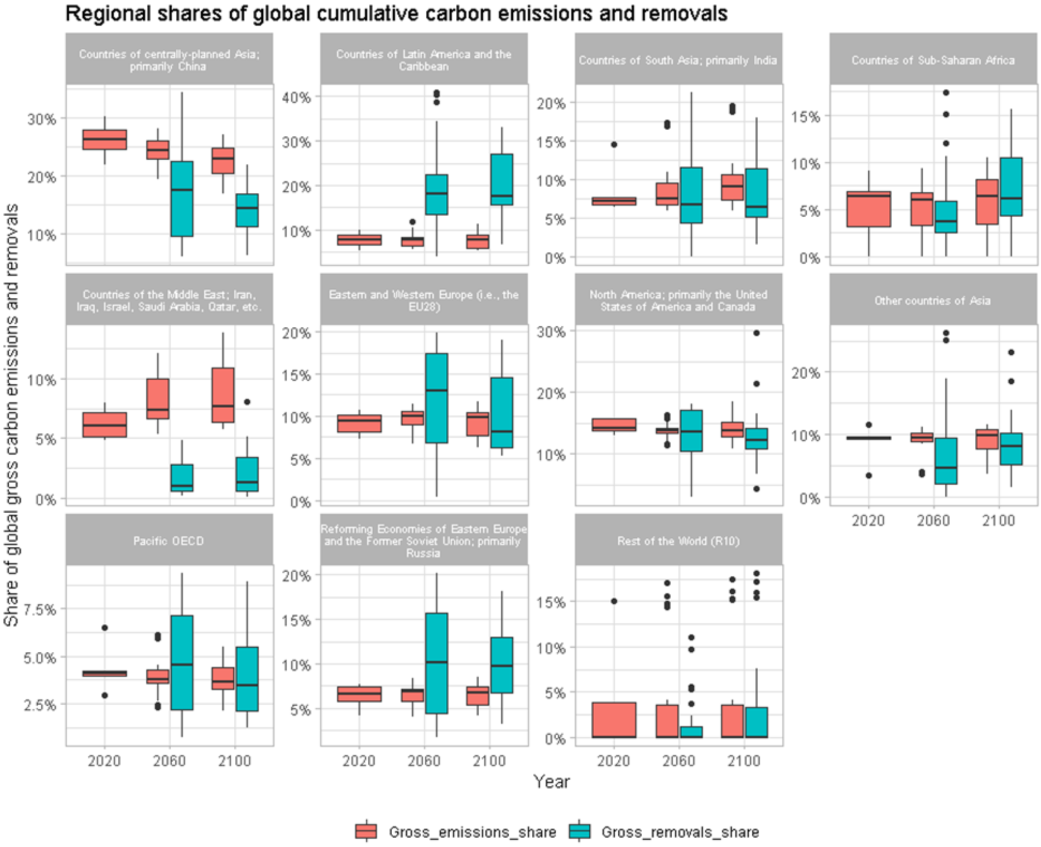

Figure 16: Regional share of global carbon emissions (red) and removals (blue) in 2020, as well as for the 2020-2060 and 2020-2100 periods.

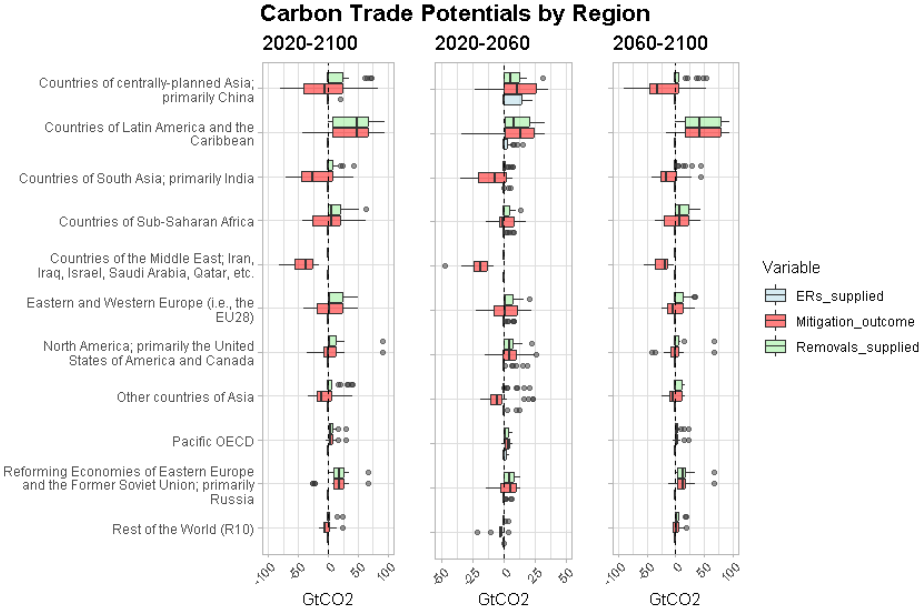

Figure 17: Carbon trade potentials utilizing a "regressive" burden sharing arrangement: Regions are allocated a portion of the global remaining carbon budget corresponding to their carbon emissions share in 2020, inherently benefiting high-emitting regions. The regional carbon budgets for 2020-2060 and 2060-2100 are determined by multiplying global cumulative net emissions within these time frames and in each variant of each scenario ensemble by the respective regional share.

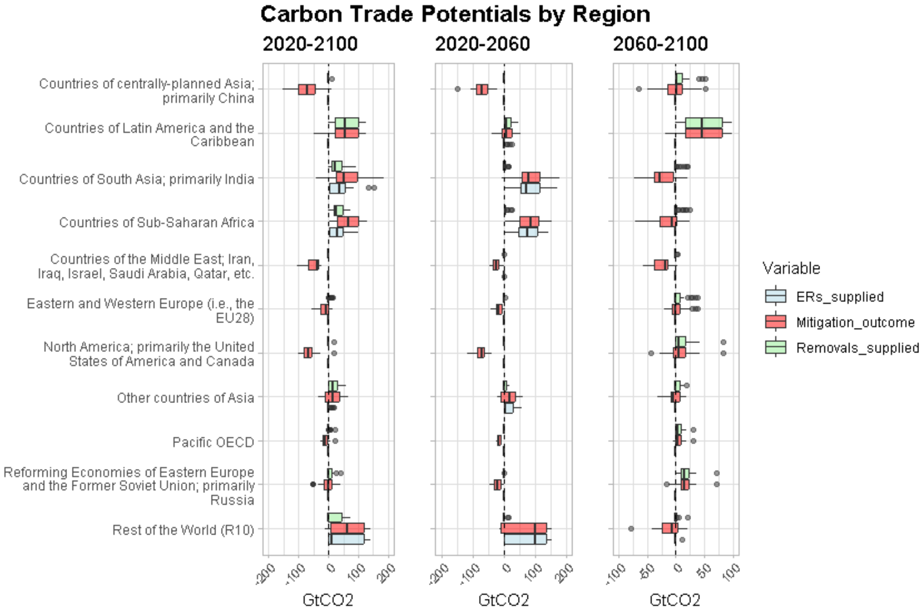

Figure 18: Carbon trade potentials utilizing a population-weighted burden sharing arrangement: Regions are allocated a portion of the global remaining carbon budget corresponding to their average population share in the 2020-2100 period, benefiting developing regions with low per-capita carbon footprints. The regional carbon budgets for 2020-2060 and 2060-2100 are determined by multiplying global cumulative net emissions within these time frames and in each variant of each scenario ensemble by the respective regional share.

7.6 Mitigation deterrence

This chapter integrates findings from our scenario analysis with key insights from a Carbon Gap report by Höglund, Delerce, and Mitchell-Larson (2023). The report investigates mitigation deterrence in various carbon removal contexts and offers tailored solutions to help policymakers address associated risks (Figure 19).

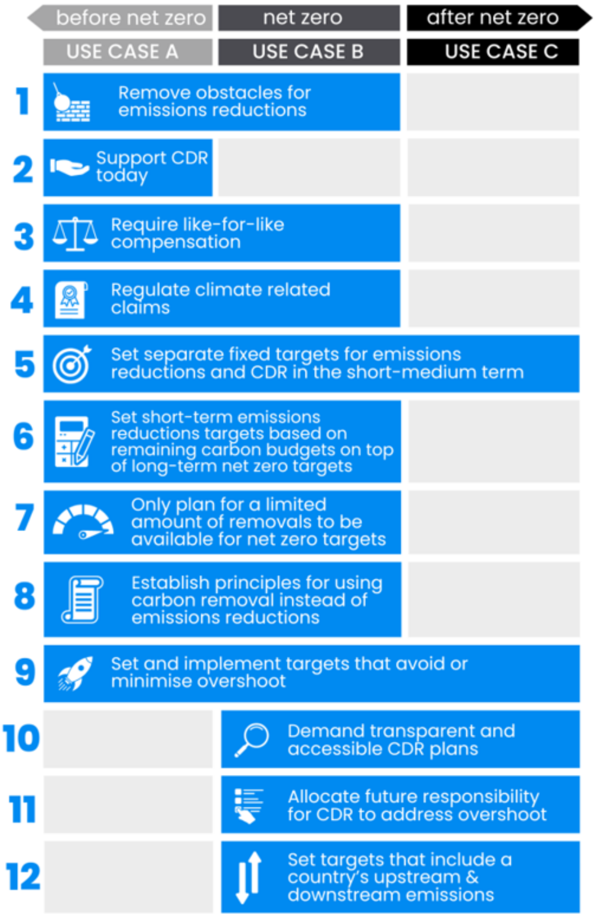

Figure 19: Summary of solutions for managing mitigation deterrence as proposed by Höglund, Delerce, and Mitchell-Larson (2023).

7.6.1 Sources and quantification of deterrence in the context of mitigation scenarios

The metric for deterrence matters

As suggested by Figure 9, deterrence, or delay of mitigation efforts, can occur in emission reductions (Scenarios 3 and 4), in removals (Scenarios 2 and 4) or both (Scenario 4). Therefore, it is essential to understand the choice of deterrence metric. As detailed in Figure 20, we define three metrics:

- **Decarbonization Deterrence (excluding CCS)** in Panel 1. This metric gauges the delay in "conventional emission reductions", i.e., resulting from the transition to renewables, biomass, and nuclear, combined with reductions in final energy demand and reductions in industrial process emissions.
- **Decarbonization Deterrence (including CCS)** as shown in Panel 2. On top of conventional emission reductions, this also includes CCS on fossil energy and industrial process emissions.
- **Mitigation Deterrence** portrayed in Panel 3. This accounts for carbon removals alongside conventional ERs and CCS, thereby implicitly quantifying the overshoot.

All these metrics measure additional cumulative emissions due to delays in decarbonization or mitigation from 2020-2050 relative to the benchmark set by Scenario 1 – Proactive Transition.

When observing Scenario 2, minimal decarbonization deterrence (excluding CCS) is found due to a decreased rate of land-use emission reductions compared to Scenario 1. However, when factoring in the initial lack of CCS incentives in Scenario 2, its deterrence level peaks to about 100 $GtCO_2$ as seen in Panel 2. This contrasts with Scenario 1 which also increases zero-emission primary energy sources at the fastest possible rate but utilizes CCS for residual fossil fuel emissions – a strategy absent in Gradual Realization (Scenario 2). When also considering carbon removals, Scenario 2's mitigation deterrence broadens further (Panel 3), primarily because of its deferred deployment of removals. In both Scenarios 3 (Unified Market Approach) and 4 (Delayed Decarbonization), we observe considerable deterrence across all metrics. In Scenario 3, the uniformity across all three metrics suggests that the main deterrence is in decarbonization (emission reductions) rather than in removals, consistent with our observation that early CDR ramp-up is a feature of this cost-effective approach. In contrast, while Scenario 4 initially trails in emission reductions, it matches Scenario 3 in terms of cumulative emission reductions by 2050. However, it falls short in ramping up removals, leading to a higher mitigation deterrence compared to Scenario 3.

As Höglund, Delerce, and Mitchell-Larson (2023) outline, deterrence can stem from various causes. In Scenario 2, deterrence arises due to a delayed political realization of the importance of CDR for meeting the Paris climate goals. Scenario 4 experiences deterrence as a result of a general delay in climate mitigation, as indicated by our metrics. However, in its original, economic sense, deterrence is characterized by both contemporaneous and intertemporal substitutions of emission reductions with removals (Fankhauser & Hepburn, 2010). This specific type of deterrence is observable only in Scenario 3, where such substitutions are permitted within an idealized integrated intertemporal market for emission reductions and removals.

Contemporaneous vs. intertemporal substitution as main mechanism of deterrence

Two main substitution mechanisms are identified:

- **Contemporaneous substitution** where emission reductions are replaced by carbon removal occurring concurrently. This could also, depending on the deterrence metric, mean conventional emission reductions being replaced by CCS.
- **Intertemporal substitution** implies emission reductions in the near-term are substituted by future removals. This is the main driver in overshoot scenarios.

In the Unified Market Approach Scenario, these two phenomena are observed in parallel. Firstly, there is a contemporaneous substitution: when CCS and carbon removal prove more cost-efficient than emission reductions, they are opted for, as shown in Figure 9. Here, the uptick in carbon removals and sequestration during 2020-2060 partially counters the decline in emission reductions within the same timeframe. Secondly, an intertemporal substitution is visible, where fewer emission reductions from 2020-2060 are partially offset by heightened carbon removals between 2060-2100, suggesting that future removals might be more economically viable in present value terms.

In this context it is important to distinguish between CCS and carbon removals. CCS partially replaces conventional decarbonization efforts at the same point in time. Conversely, carbon removal can replace emission reductions both contemporaneously and intertemporally.

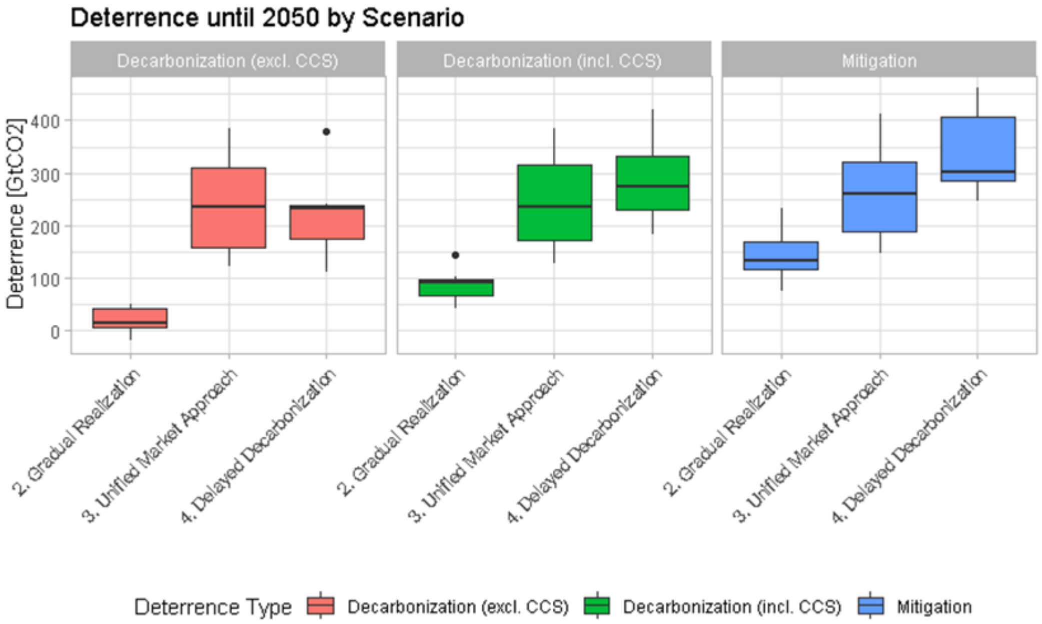

Figure 20: Quantifying mitigation deterrence using three different metrics. Panel 1 captures the delay in decarbonization from replacing fossil fuels with other sources of primary energy, as well as from reducing final energy demand and industrial process emissions. Panel 2 also includes fossil CCS and CCS for industrial process emissions. Panel 3 includes carbon removals. The presented numbers are additional cumulative CO_2 *emissions in the 2020-2050 period due to deterrence.*

7.6.2 Regulation for minimizing deterrence

Implement separate policies and limit fungibility between ERs and CDR

Scenario 3 is based on a unified market and/or policy approach for emission reductions and carbon removals, thus replacing emission reductions with carbon removals both contemporaneously as well as intertemporally, whenever this reduces costs. This illustrates that full fungibility between emission reductions and carbon removals, or a lack of rigorous regulation can induce various types of deterrence through CCS and carbon removals. To mitigate this, it is imperative to establish distinctly separate policy frameworks for emission reductions and for carbon removals. For CCS it is necessary to have an objective evaluation and open discussion whether this technology rather falls in the domain of emission reductions or carbon removals.

The importance of countering intertemporal substitution of near-term emission reduction with speculative future removals through the adoption of separate policies as well as targets for emission reductions and carbon removals has been underscored by a breadth of voices, including academic perspectives (McLaren, Tyfield, Willis, Szerszynski, & Markusson, 2019), expert recommendations (Geden & Schenuit, 2020; Dorndorf, Friis, & Carton, 2021; Geden, Peters, & Scott, 2019) and even industry insiders (Climeworks, 2023). However, adopting such a strategy may come with economic efficiency trade-offs (Smith S. , 2021).

For emissions trading, approaches to manage mitigation deterrence risks also includes limiting the fungibility between emission reductions and carbon removals. Beyond the short-term this includes also novel CDR methods with long-lasting or permanent storage. Moreover, implementing distinct price paths for emission reductions and removals proves advantageous for various other reasons: a higher price for CDR in the near term is beneficial to incentivize learning and encourage technological uptake, while a lower price path in the long run is strategic to prevent excessive profits within the CDR industry and resultant welfare distributional considerations (Andreoni, Emmerling, & Tavoni, 2022) as well as to alleviate the fiscal burden in case net removals transition into a public waste management task (Bednar, Obersteiner, & Wagner, 2019).

Hybrid policy approaches are also possible where governments designate sectors eligible for carbon removal offsetting. Since the technologies for both emission reductions and carbon removal evolve quickly, it is important that principles and frameworks allow for adaptation to changing circumstances. However, there is a trade-off between policy adaptation and market player trust to be considered. Once investors have sunk costs, they are sensitive to changing rules.

Account for externalities of emission reductions and removals

An unnecessarily large degree of contemporaneous substitution could cause unintended side effects, like excessive land or resource use through carbon removals. One proposed solution to target this is to develop principles for when it is preferable to deploy carbon removal versus emission reductions. As Höglund et al. (2023) suggest, this decision should weigh the relative cost, availability, side effects, and co-benefits of carbon removal methods compared to emissions reduction options. However, implementing such principles could require extensive top-down control to steer which specific emissions are offset by what types of carbon removal. This level of governance may not be realistic in many contexts. A part of the solution might, however, be the pooling of various types of carbon removals into standardized removal units, for which standards for permanency, negative externalities, and co-benefits could be established (Macinante & Singh Ghaleigh, 2022).

Incentivize near-term ramp-up of CCS and CDR aiming for ambitious climate mitigation milestones

Specifically, the Proactive Transition Scenario, with its early and aggressive investment in carbon removal/CCS meeting ambitious near-term climate mitigation targets, is designed not to replace emission reductions but to complement them, which effectively minimizes deterrence across all metrics (making it the benchmark in this comparison). By advocating for the early integration of CCS and carbon removal, learning is enhanced, and economies of scale are realized, allowing for a gradual decline in incentive payments over time. This is vital to subsequently reduce the overshoot and its inherent risks. Short-term carbon removal ramp-up goals also ensure that carbon removal solutions start to be built out today, alleviating some of the risk that enough carbon removal does not materialize to meet the future needs.

In Scenarios 1, 2, and 4, pricing of carbon removal and CCS is separated from emission reductions, yet only in Scenario 1, which maximizes the climate mitigation outcome, carbon removals are seen as a complementary and essential near-term strategy to achieve net-zero and to minimize a climate overshoot. In this sense, Scenario 1 – Proactive Transition – is the first best scenario in terms of the climate mitigation outcome as it maximizes the use potential of all permissible technologies represented in the dp-IAM literature. Economic viability of this scenario compared to the other pathways is increased if overshoot risks are properly priced in; if learning rates are larger than anticipated; and if the currently assumed market interest rate of 5% in dp-IAMs is decreased.

A policy proposal advocating for the near-term ramp-up of CCS and carbon removal introduces the "Carbon Takeback Obligation" (Jenkins, Kuijper, Helferty, Girardin, & Allen, 2023). According to this proposal an increasing share of fossil fuel emissions would be directly captured at the source by CCS or offset by carbon removals with permanent storage. However, while such an approach might be appealing for its simplicity to reach net-zero, it does not address the issue of overshoot reversal. Additionally, it limits the ability of policymakers to regulate the desired balance between substituting emission reductions with CCS and carbon removals in the present.

Manage the climate overshoot

Recognizing the role of intertemporal substitution is fundamental in integrating carbon removals into climate policy. Even without intertemporally operating carbon markets, intertemporal substitution still occurs. The mere discussion of future, speculative CDR as a fallback option can inadvertently lead policymakers to lessen the urgency of immediate, robust climate actions, relying on this speculative 'plan B' and thus undermining the efforts towards rapid emission reductions. Additionally, a feedback loop exists through exploratory modelling with dp-IAMs, as seen in the IPCC's 5th Assessment Report, which illustrated numerous cost-effective overshoot scenarios akin to Scenario 3 – Unified Market Approach. These modelling outcomes, when disseminated through channels like the IPCC, can influence current climate target setting (Bednar J. , et al., 2021).

A straightforward approach to reduce intertemporal substitution is the determination of clear emissions reduction targets aligned with remaining carbon budgets (Höglund, Delerce, & Mitchell-Larson, 2023). Such short-term goals provide guardrails alongside mid-century net-zero targets, and prevent that reductions are pushed to the future. However, this approach must be coupled with strategies for overshoot reversal, which is intrinsically connected to intertemporal substitution. Considering the narrowing window to avoid surpassing the 1.5°C warming threshold (Lamboll, et al., 2023) —substantially less than a decade—an overshoot appears unavoidable. Policy balance is thus crucial: it should permit a degree of managed intertemporal substitution to handle the inevitable overshoot and its reversal while avoiding excessive deterrence or extreme temperature overshoots. The Polluter Pays Principle, enshrined in the Treaty on the Functioning of the European Union (TFEU), has been proposed as a foundation for such policy. Rigorous application of this principle would mean, firstly, that each tonne of CO_2 emitted mandates a corresponding removal by the emitting entity, especially once the carbon budget is exhausted. Financial responsibility for future carbon removals, intended to offset present emissions, should equitably fall upon near-term or historical emitters according to this principle. Secondly, emitters should pay for temporary atmospheric carbon storage, referring to the period during which emitted CO_2 remains in the atmosphere before being removed by natural processes or technological solutions. During this time, the CO_2 contributes to global warming and increases the risk of triggering adverse climate feedbacks and accruing climate damages. To account for these risks and incentivize prompt removal, it is essential to price this temporary atmospheric carbon storage. This pricing mechanism aims to reduce moral hazard by ensuring that emitters take financial responsibility for the immediate impacts of their emissions, thereby addressing loss and damage attributable to overshot emissions. This concept is integral to the policy framework of 'Carbon Removal Obligations', detailed further in Chapter 10.

Manage low-integrity carbon removal

One key concern is the use of low-integrity carbon removal to offset continued fossil fuel use, compromising climate integrity. This can be solved through the principle of like-for-like removal, where the permanence and durability of carbon storage match the emission source (Allen, et al., 2022). Under this principle, fossil carbon must be compensated with permanent geologic storage, but short-lived emissions such as methane could be offset by temporary carbon storage (Allen, et al., 2022; Hickey, Fankhauser, Smith, & Allen, 2023; Höglund, Delerce, & Mitchell-Larson, 2023; Höglund & Lockley, 2023).

For emissions trading, limiting the fungibility between emission reductions and carbon removal units is vital to prevent present-day emission reductions from being replaced by low-integrity removals.

Advocate for transparency

Ensuring transparency in outlining plans for reductions and removals is vital to uphold the integrity of mid- to long-term targets. Specifically, clarity is required on aspects like whether a net-zero commitment pertains solely to CO_2 or encompasses broader GHGs, the extent to which it relies on carbon removals, and whether these removals are primarily land-based or hinge on enduring geological storage (Rogelj, Geden, Cowie, & Reisinger, 2021).

7.7 A broader perspective on factors affecting CDR deployment – barriers and trade-offs

Smith et al. (2023) in their state of CDR report identify a large implementation gap. While conventional nature-based CDR methods are seeing sizeable market shares in the VCM, country level implementations are highly variable and vulnerable to policy changes and novel CDR methods are still in the research and demonstration phase. The barriers to implementation are typically highly technology and location specific. All CDR methods currently face an uncertain policy environment. Carbon removal is about rather complex technology bundles that are characterized by large sunk cost and lock-in decisions (particularly in land use or CCS infrastructure). In the absence of clear long-term policies, supportive regulatory frameworks and financial incentives sunk costs today might become stranded assets at a later stage deterring investors from larger scale investments supporting scaling of these technologies. Current policy frameworks in many countries do not incentivize or sometimes even allow for the deployment of certain CDR methods. Here we will shortly discuss the barriers separated by NbS and novel CDR methods, using example CDR methods to illustrate.

7.7.1 Barriers and trade-offs for conventional Nature-based Solutions

Nature-based Solutions (NbS) typically carry the potential to address numerous social and environmental challenges which makes them more complex to manage. The most important complexities constraining mostly the scaling of NbS is **land tenure and property rights**. Many countries have not clarified land tenure and established land tenure systems. Securing rights to the land as well as the rights of particular ecosystem services, such as carbon sequestration, are still faced with many troubles. In addition, the system of establishing property rights to carbon benefits by nature is still plagued with incidents of "**greenwashing**", where entities falsely claim environmental benefits such as avoided emissions from deforestation. More elaborate and stringent certification and verification processes are needed to establish more credible baselines against which climate benefits can be established as well as consideration of so-called leakage (see section 8.2). There are also potential **social and environmental trade-offs** among NbS, such as biodiversity loss, water scarcity, food security and income in favour of carbon sequestration (Obersteiner et al., 2016) (Smith, et al., 2019). Comprehensive environmental assessments and stakeholder engagement at national was well as on project scale will help minimize these trade-offs. On the national scale the FABLE initiative provides an opportunity of countries to engage in a network of countries to jointly assess how policy interventions could overcome barriers and support the management of trade-offs in the land use decision making.

Another obstacle is the lack of **awareness and understanding** about NbS among policymakers, businesses, and the general public. This is closely linked to **economic barriers that** also deter the adoption and swift scaling of NbS across landscapes. Most important here is that upfront costs (including cost of time for permitting and licensing) are typically high and can seem higher than for traditional approaches such as establishing conventional timber plantations. To overcome the economic barriers, its essential to integrate the valuation of ecosystem services into cost-benefit analyses and establish financial incentives or grants to compensate for nature up-lifts and mitigate upfront costs problem essentially leading to stranded land asset risks by improved and more stable policy support. **Robust institutional and regulatory environments** are needed to establish conducive policies promoting NbS are needed which will also necessitate enhanced inter-departmental coordination on the (international)national policy level. Such coordination will always prove to be high in transaction cost and be slow pointing to constraints for scaling. In addition, these measures will need to be bundled with investments into overcoming challenges of technical and knowledge gaps providing training, fostering research partnerships, and supporting capacity-building programs. Finally, **MRV** of NbS projects pose challenges due to the dynamic and uncertain nature of ecosystems. Standardized frameworks and technological tools like remote sensing and modelling of ecosystem dynamics can help overcome this barrier.

7.7.2 Barriers and trade-offs for novel CDR methods

Barriers and trade-offs for novel CDR methods fall into two broad separate categories of CCS based (BECCS, DACCS) and mineral rock based enhanced weathering on land and ocean alkalinization. A holistic assessment of large-scale deployment of these technologies is rather different. DACCS is much less land intensive, but much more energy intensive and still prohibitive in costs (Honegger, Michaelowa, & Roy, Potential implications of carbon dioxide removal for the sustainable development goals, 2021). The Scaling of DACCS, thus, will mainly depend on energy supply conditions in the vicinity of the DACCS plant as well as the availability of the geological storage sites. Remote places with ample supply of renewable energy from solar, wind, and geothermal and with sufficient CO_2 transport and storage infrastructure are likely to see cost advantages and might be able to scale once they become cost competitive. The fact that DACCS is highly compatible with fossil fuel industry long-run strategies, potentially mitigating existential risk concerns, in terms of technology integration, finance approaches and infrastructure utilization cost seems to be the single largest barrier next to regulatory risks relating to mitigation deterrence and public acceptance. Bioenergy with Carbon Capture and Storage (BECCS) and afforestation/reforestation can require significant land and water resources, which might compete with food production and natural ecosystems (Smith, et al., 2019; Honegger, Michaelowa, & Roy, Potential implications of carbon dioxide removal for the sustainable development goals, 2021). The intensity of competition for land depends on the success of the food system to reduce its land footprint (Obersteiner et al. 2016). The potential to reduce the footprint is in fact enormous, potentially freeing up large amounts of land for restoration which might become a new and more ecological source of biomass supply and not compete with food security (Folberth, et al., 2020; Vittis, Folberth, Bundle, & Obersteiner, 2021). A challenge which is shared by DACCS and BECCS is that CCS at scale would require that the different components along the value chain be developed (and incentivized through policy) jointly to avoid cross-chain risks and potential associated potential "hold-up" or "commitment" problems (Möllersten, Marklew, & Ahonen, 2023). A given industrial actor is unlikely to want to invest heavily in capture equipment before knowing that there is storage with sufficient capacity available. Conversely, a storage operator is unlikely to commit heavily into CO_2 injection and storage capacities without knowing that there will be capture plants prepared to deliver CO_2 and pay for its storage. Strategic coordination of infrastructure development, including CO_2 transportation solutions, will be a crucial element in achieving the ramp-up required to achieve the massive CDR capacities that will be necessary.

Rock powder application to soils and oceans is an even more nascent CDR technology, and the full range of their environmental impacts are not yet fully understood (Fuss, et al., 2018). Ocean Alkalinity Enhancement (OAE) involves adding alkaline materials to the ocean. This process increases the ocean's capacity to absorb and store CO_2 as bicarbonate ions. For OAE to have a meaningful impact on atmospheric CO_2 levels, enormous quantities of alkaline materials would need to be added to the oceans. The sheer scale and the total costs of the required operation poses logistical, energy and financing challenges in terms of sourcing, processing, and distributing the materials (Honegger, Michaelowa, & Roy, Potential implications of carbon dioxide removal for the sustainable development goals, 2021). Introducing large amounts of alkaline materials could have unforeseen and potentially detrimental impacts on marine ecosystems. Changes in ocean alkalinity could affect marine organisms, especially those that rely on calcium carbonate for shell and skeleton formation. There are also still challenges around the monitoring of the carbon benefits of OAE and its potential side effects over vast ocean areas. Thus, large-scale geoengineering projects related to OAE are likely to face scepticisms or resistance from the public due to concerns about unintended consequences. In addition, legal and regulatory hurdles are far from being sorted. Enhanced weathering is still a rather underestimated technology that might have a number of interesting co-benefits ranging from soil fertility recovery to increased water holding capacity (Honegger, Michaelowa, & Roy, Potential implications of carbon dioxide removal for the sustainable development goals, 2021). Trade-offs that have been identified are with heavy metal pollution, potential overuse of fossil fuels in the mining, grinding and transportation stages as well as health effects due to dust spread (Janssens, et al., 2022; Goll, et al., 2021; Eufrasio, et al., 2022). MRV systems to quantify the atmospheric benefit are still in research stage, however, show promising results for widespread accurate application.

Box 1: The efficiency of DACCS as CDR method.

A note on DACCS

Only Scenarios 3 and 4 in this report include DACCS at significant levels. The energy demands of DACCS bring into question its effectiveness as a CDR method. Specifically, DACCS demands more energy to extract CO_2 from the air than what was originally released during the burning of the fossil fuels that produced it. The idea of utilizing fossil fuels to power DACCS is counterintuitive: each tonne of CO_2 captured by DACCS means more than one additional tonne of CO_2 needs to be captured and stored due to the fossil energy consumption and its CCS efficiency. Thanks to their proximity to empty extraction sites, fossil fuel companies may have infrastructural efficiencies that could simplify and potentially decrease the expenses associated with CO_2 storage in DACCS. However, directly applying CCS to unabated sources of fossil fuel emissions is more efficient in terms of thermodynamics. In the special case where CO_2 from DACCS is used for enhanced oil recovery another mitigation deterrence loop will be opened.

An alternative energy source for DACCS could be hydrogen produced from intermittent renewable energy or direct usage of geothermal power. Yet, this could divert these energy sources from other direct emission-reducing roles, such as using hydrogen in sectors like industry or long-haul aviation and shipping. Hence, for DACCS powered by renewables to make a difference, the larger economic environment must be operating close to zero-carbon emissions, i.e., when conventional mitigation potentials are depleted. This is essentially the case in the second half of the century in our scenarios, when emissions turn net negative to revert an overshoot. Hence, DACCS could play a role as a long-term strategy contributing to a net negative carbon economy.

In assessing DACCS, one question emerges: Would the energy set aside for DACCS be better spent on directly reducing carbon emissions in the economy? From a physics standpoint, direct emission cutbacks are always more efficient. DACCS becomes a rational choice only in the absence of unabated fossil fuel emissions or when there exists an energy source exclusively viable for DACCS and not for other emissions-reducing applications. From a technological learning point of view, it is inevitable that DACCS will create inefficiencies during learning and ramp-up phases. However, early deployment of DACCS exclusively powered by renewables could lead to accelerated cost declines of renewables and make them more competitive in the long-run not only in combination with DACCS while increasing costs for renewables in the short-run. Respective learning rates have not yet been investigated.

8 CDR methods and risk of reversal and leakage

8.1 The comparability of different types of CDR methods based on durability

There is a difference between carbon capture and carbon storage in the carbon dioxide removal process. Carbon captured through one method can be stored in many different ways (see also section 3.2 for a more detailed explanation). For example, carbon captured in biomass (through photosynthesis) can be stored in living biomass (e.g., through afforestation or reforestation), burnt for energy with the CO_2 captured and stored geologically (BECCS), or pyrolyzed into biochar and applied to soil or used in durable products. In this section we explore the durability of storage methods.

Carbon storage longevity is often talked about as permanent or temporary, but there is a need for a more nuanced vocabulary. Some storage methods keep the carbon temporarily for hundreds of years, whereas others have a high risk of reversal but could in theory last for millennia. More precision in classification allows better comparison of storage options. Höglund (2022) laid out a new storage classification that distinguishes between (Figure 21):

- Permanent storage, with no practical risk of reversal.
- Stable storage with some, but very low risk of reversal (for example in geologic reservoirs).
- Long-term temporary storage (ocean sinks, biochar), gradually released over centuries/millennia.
- Vulnerable storage with a medium to high risk of reversal (biomass, soils, products).
- Short-term temporary storage where the carbon is lost after a few years to decades.

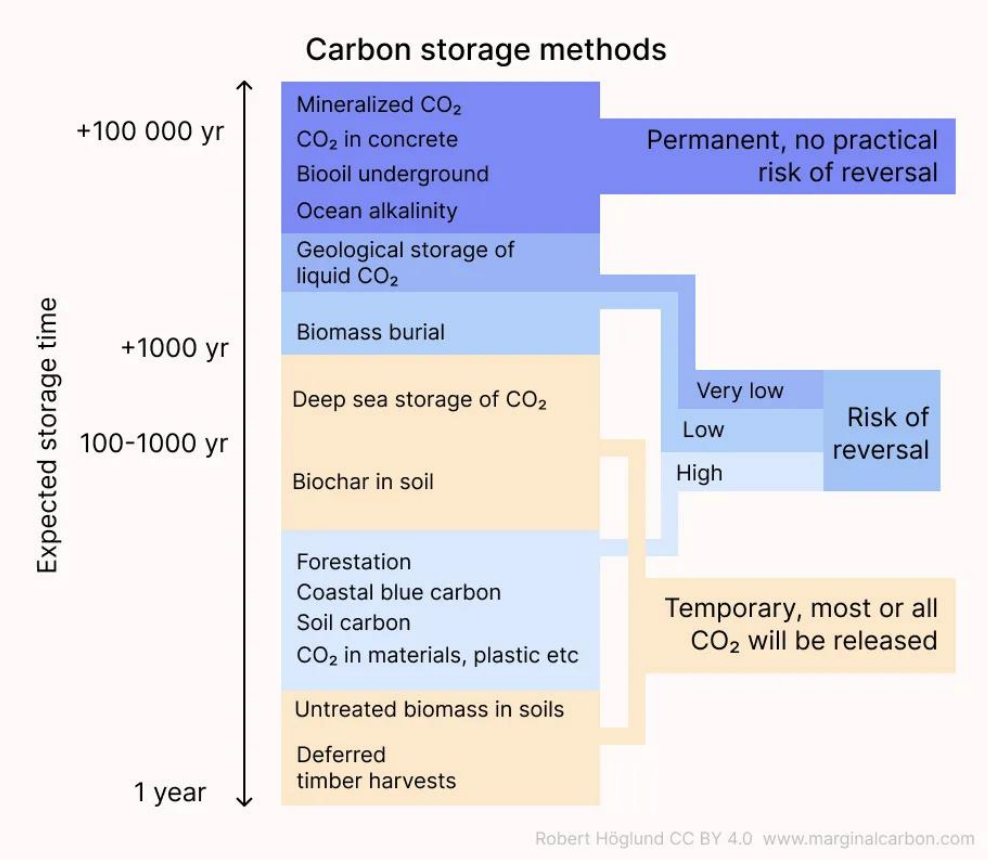

Figure 21: Carbon storage classification. Source: Höglund (2022). For sources to the expected storage time see appendix X https://docs.google.com/spreadsheets/d/1basgpfYMu9DIZfIFJqfHS3d0NLZfkpZvFhrPPJDXRt0/edit#gid=13434633.

8.1.1 Expected storage time

A useful concept is that of ‘expected storage time’ which considers risk of reversal as well as the eventual gradual re-release of carbon. The calculation for expected storage time will be different between inherently temporary carbon storage solutions and those that have a risk of reversal.

For storage with no practical risk of reversal, such as mineralized CO_2, the expected storage time is infinite from an anthropogenic viewpoint.

For storage with a very low risk of reversal, such as supercritical CO_2 stored in geological formations, the expected storage time has been calculated using the risk and magnitude of CO_2 leakage. Over time, the CO_2 stabilizes and is finally mineralized. According to the IPCC (2005), the expected fraction of CO_2 retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years. For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilized by various trapping mechanisms and, in that case, could be retained for up to millions of years.

For carbon storage with a medium to high risk of reversal, like forests, expected storage time depends on specific risks that differ globally. For example, fire risk is much higher in some regions than others. Contract length for reforestation is sometimes used as an estimate for expected carbon storage time. However, this does not fully capture the complexities involved: When a contract ends, the risk of reversal spikes as legal protections lapse, but the carbon is not necessarily lost immediately. Forests may remain after a contract ends if not part of a commercial forestry plantation. Estimates for expected storage time could combine contract length, gradual sequestration rates, potential regrowth after a loss, possible magnitudes of loss (partial reversal is possible) and region-specific annual reversal risks to model more nuanced expected storage timelines. For the carbon storage methods in this category, more research is needed to precisely estimate those parameters. A single number for expected storage time would in any case not be possible to give, but could be expressed in probabilities (i.e., x% chance y% of carbon remains after z years), but such probabilities make comparisons with other CDR methods difficult.

For inherently temporary storage, durability can depend on both gradual versus sudden release. Deferred harvest for example has a sudden release of all the carbon after a set contract length. This typically ranges from 1 to 10+ years subject to agreed terms. Biochar on the other hand decays gradually. According to studies, the estimated fraction of remaining carbon is approximately 80% of the carbon after 100 years, 50% after 500 years, and 25% after 1000 years (under common conditions) (Woolf, et al., 2021). However, this depends on factors such as biochar stability, and soil temperature and acidity. There are also indications that biochars have stable components that do not degrade, making part of the carbon in biochar permanent, but this is yet to be proven (Schmidt, Abiven, Hagemann, & Meyer zu Drewer, 2022; Sanei, et al., 2024). Similarly, parts of carbon stored in the deep seas, for example as an effect of biomass sinking, is gradually released as CO_2 as the ocean layers overturn after hundreds to thousands of years (IPCC, 2005). Storage with gradual decay could be expressed with mean residence time (MRT). For example, biochar with the decay rates described above would have a MRT of ~250 years.

8.1.2 How can short-lived and permanent carbon storage be compared?

Removing CO_2 from the atmosphere and temporarily storing carbon does not mitigate long-term temperature change. The long-term temperature change is predominantly driven by cumulative CO2 emissions and is insensitive to the timing of those emissions (Canadell, et al., 2021). Limiting global warming is one of the primary goals of the Paris Agreement, which entails maintaining cumulative emissions below the threshold at which temperature goals are exceeded. Approaches that apply discounting future emissions associated with temporary carbon storage[20], enable reporting entities to effectively claim that they are operating within a given carbon budget, or have achieved net-zero emissions, when this is not the case (Brander & Broekhoff, 2023). It is, therefore, advisable that emissions and removals must be reported without discounting to ensure that GHG accounts accurately reflect contribution to cumulative emissions.

Physical climate equivalence thus requires that the length of time carbon is stored is comparable to how long CO_2 lasts in the atmosphere. All else equal, utilizing temporary carbon storage methods instead of permanent result in higher future temperatures, but could still be desirable if the expired storage is replaced, the harm from warming decreases over time, or future harm is discounted. If these conditions are not met, then no amount of short-term storage can be equated with permanent storage (Höglund & Lockley, 2023).

Discounting relies on a cost-benefit optimization approach, which is incompatible with temperature targets and the Paris Agreement. Carbon that is not stored past peak temperatures have limited value from temperature perspective as they do not contribute to reaching it. That is a key conclusion of Cullenward (2023). As Cullenward writes: “This policy objective [The Paris Agreement] effectively prioritises a cost-effectiveness framework (which seeks to achieve the stated goal with minimum costs) above the alternative economic paradigm of cost-benefit optimization (which tends to prioritise near-term climate benefits at the expense of higher long-term warming outcomes).“. Temporary storage with CO_2 re-released before peak temperatures still has some value, just not for reaching the targets.

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[20] Typically, such that carbon stored temporarily can be accounted for as a fraction of permanent reduction in emissions of a corresponding magnitude.

Short-term carbon storage re-released after peak temperatures are reached does contribute to temperature targets to some extent. However, it is still not physically equivalent to permanent storage if eventually rereleased. The longer CO_2 is stored past peak temperatures, the higher its value.

Matthews et al. (2023) show that temporary storage can help to reduce global warming, but only when renewed so that it lasts past peak temperatures. They conclude that if temporary storage is used to offset fossil emissions, it does not lead to lower temperatures. In the article they propose using tonne-year accounting to keep track of temporary storage but criticise how the concept has been used previously trying to equalise temporary storage to permanent. As they write: "Using an equivalency factor to infer the climate benefit of temporary carbon storage produces a time series of presumed temperature benefit that bears almost no resemblance to the actual avoided warming that results from temporary storage".

Strategies for handling vulnerable or temporary storage

If short-term carbon storage is continuously renewed with new short-term storage, or once with permanent storage then the climate benefit remains. This approach might be favoured if the combined cost and overall benefits of temporary storage and future replacement is less than the immediate cost of permanent storage.

Table 4: Potential benefits and disadvantages of utilising temporary or vulnerable storage.

Benefits	Disadvantages
Lower upfront costs compared to permanent storage	Requires planning and incentives to ensure future replacement
Takes advantage of nature-based carbon removal methods with possible co-benefits.	Replacement costs may be higher in the future
Potentially provides time to scale up permanent storage methods	Administrative burden of tracking credits and ensuring renewal
Can spread costs over time compared to entirely permanent methods	Risk of bankruptcy of the project owner, or buyer of credits if a company, or discontinued oversight before renewal.
	Monitoring reversals in some systems is challenging.
	May disincentivise investments in permanent removals, inhibiting its growth.

8.2 Framing leakage in relation to carbon dioxide removal

Leakage is defined as the net change of GHG emissions or removals that are attributable to a mitigation activity but occur outside the boundary of that activity. These include, for example, indirect emission changes upstream or downstream of the mitigation activity or rebound effects. The robust quantification of emission reductions of project activities requires that leakage is detected and taken into account in order to secure that emission reductions or carbon removal is not overestimated (Schneider, et al., 2020).

Broekhoff, et al. (2019) identify high risks of leakage in the following project types that encompass or are relevant in relation to CDR:

- Low-till/no-till soil carbon sequestration. Leakage risk can be a significant issue for tillage projects to the extent crop yields are affected.

- Biomass energy (including agricultural farm residue, forest residue, and dedicated energy crop). Significant risks of over crediting concern due to lack of assessment of land use, as well as direct and indirect land use change from collection of biomass feedstocks. Although the authors to not specifically point out any CDR applications, the use of biomass for BECCS and biochar carbon removal belongs in this category.

- Forestry and land use (A/R; avoided deforestation; improved forest management; agroforestry; avoided conversion of high-carbon soils). Significant leakage risk can occur from displacement of harvesting or land-use development (i.e., reduced harvest in one area can cause an increase elsewhere).

It is noticeable that all the project types identified are land use-related. There is an abundance of literature addressing leakage risks in relation to activities that have an impact on land use. Governing land use is challenging, because land use systems are complex with drivers operating directly and indirectly through dynamic interactions and feedbacks. One type of indirect effect is the displacement of land uses to near or remote sites, often described as spillover effects. Meyfroidt et al. (2018) define land use spillovers as “the process by which land-use changes or direct interventions in land use (e.g., policy, program, new technologies) in one place have impacts on land use in another place”. These effects are difficult to measure, particularly when economic markets are implicated (so-called market leakage) (Meyfroidt, et al., 2020). Spillover effects can lead to both positive (reinforcing) and negative (counteracting) social and environmental impacts.

Leakage may be defined by the following three key elements (Meyfroidt, et al., 2018):

1. There is a causal linkage from an environmentally-related intervention.
2. The leakage-affected outcome variable is the same as the targeted outcome of the intervention, although in a different domain—i.e. in another place, through other actors, or through other land uses or commodities.
3. Leakage (sensu stricto) has a negative (counteracting) effect on this variable.

The taxonomy that has evolved surrounding leakage furthermore includes a differentiation between ‘weak leakage’ and ‘strong leakage’, where the latter would correspond to the above definition while “weak leakage” represents cases where there is a less clear causal attribution between the leakage-affected outcome and the environmentally-related intervention.

As already mentioned, interventions may have positive and/or negative spillovers. Some authors have thus used ‘inverted leakage’ or ‘positive leakage’ to refer to spillovers that have positive on impacts on the targeted outcome. Meyfroidt et al. (2020) recommend, however, that because of its negative connotation, the word ‘leakage’ is best reserved for impacts that are indeed negative and suggest referring to ‘positive land use spillover’ in other cases.

Filewood and McCarney (2023) separate leakage into two canonical types: ‘‘direct’’ leakage and ‘‘market’’ leakage. Direct (or ‘‘activity’’) leakage arises when the economic agents targeted by an intervention shift activities outside of the accounting boundary, whereas market leakage arises when non-targeted agents adjust their behaviour in response to altered economic incentives. Meyfroidt et al. (2018) identify four leakage mechanisms, which interact in reality: (1) activity leakage, (2) land market leakage, (3) commodity market leakage, and (4) supply chain leakage.

Activity *leakage* occurs when production factors or inputs are highly mobile such that labour and capital used on the land targeted by the restrictions are reallocated to places with available and accessible land. Activity leakage is more likely to occur through labour reallocation under conditions of subsistence agriculture, with lack of off-farm alternatives or cultural preferences for land-based activities, and through capital reallocation when sunk costs of capital investments in the initial place are not too large. Unfavourable conditions for intensification locally, and growing demand for the affected product reinforce this pathway by creating incentives for producers to continue production elsewhere.

Land-market *leakage* can occur, where appreciation of land rent in the affected place spreads through land markets to land situated elsewhere, driving land investments, including deforestation, in these places. In the region affected by regulations, increase in price of the non-affected land can facilitate activity leakage by providing landowners with financial capital to reinvest elsewhere. Although in principle this path can occur as leakage from policy restrictions, it is more likely to occur as a form of indirect land use change resulting from an increase in demand of a commodity.

Commodity-market *leakage* occurs when land use expands elsewhere in response to changes in product prices. The cause may be an intervention that takes place in a high-yielding region and where the conditions for intensification are not met in the different regions where production takes place. Such leakage may also occur if the affected good is substituted by more land-demanding goods.

Supply-chain *leakage*, finally, is where producers continue to produce the same good but shift to other buyers, sell their products by “laundering” them through intermediaries that are compliant with the intervention, or switch to producing another good with high environmental impacts. Supply-chain leakage may be prompted by an intervention that excludes a given good or suppliers who do not meet sustainability standards.

9 Mapping and analysis of approaches to address durability of carbon storage, leakage and MRV

This chapter discusses approaches for taking into account durability, leakage, and monitoring.

A mapping of approaches for taking durability and leakage into account in existing carbon crediting programmes is presented.[21] The five carbon crediting programmes Verra, Gold Standard, American Carbon Registry (ACR), Clean Development Mechanism (CDM) and Puro were mapped and compared based on the following:

- governance level,
- scope and eligibility,
- durability and crediting periods,
- durability mechanism,
- reversal management mechanism, and
- carbon leakage provisions.

All five crediting programmes have received endorsement from **ICROA**, showcasing their compliance with ICROA's governance and transparency standards. The Gold Standard is the only crediting program that is **ISEAL** code compliant. Carbon removals can be credited under each of the programmes. Notably, **Puro** is the only crediting program solely focused on carbon removals. The geographical scope is **global** for all compared programmes.

The main features of the considered programmes are outlined in the sections below and a detailed account of the programme mapping can be found in Table 7 and Table 8.

Furthermore, durability and leakage provisions in notable upcoming carbon crediting standards are presented.

The chapter is concluded by a section which discusses the applicability to CDR of approaches for considering durability, leakage, and monitoring.

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[21] Note that data presented is as of 1 Oct 2023.

9.1 Durability provisions in existing carbon crediting programmes

9.1.1 Durability

The crediting programs in the comparison define the durability of carbon removal in different ways, highlighting a lack of coherence. They utilise various timeframes, including a 100-year horizon in alignment with the IPCC's Global Warming Potential horizon, as well as shorter durations such as **10, 20**, **30-50**, or **40** years. These examples represent specific periods during which the carbon credits generated by a project or program are considered valid or eligible for issuance.

The most often used durability typically ranges from **20 to 40** years, with Verra requiring a minimum of **20** years, Gold Standard specifying **21** years and a range of **30-50** years for A/R projects, and ACR AFOLU mandating **40** years. However, the durability can vary based on the type of project. For Verra AFOLU and Geological Carbon Storage (GCS) projects, the storage durability ranges from a minimum of **20** years to a maximum of **100** years. In contrast, Puro establishes a minimum durability requirement of **100** years.

An evident contrast becomes apparent when comparing forest sector sequestration with other CDR methods, notably geological storage or biochar. A scrutiny of various crediting programs reveals a distinct difference in the timeframes associated with these carbon removal activities. For instance, the durability of forest sector sequestration typically ranges from **20 to 100** years (as seen in Verra's methodologies), but it is still primarily within a shorter time-period. In contrast, other CDR methods have notably longer expected storage duration, starting from **100** years (as exemplified by Puro).

9.1.2 Durability Mechanisms

Carbon crediting programs have implemented **six** distinct **durability mechanisms**. The **commitment period** during which the projects commit to maintain, monitor, and verify project activity is the most commonly used one (Arcusa & Hagood, 2023), employed by Verra, Gold Standard, ACR (for AFOLU), and Puro. ACR uses a different durability mechanism for geological sequestration projects, focusing on **demonstrating stability**. For CCS activities, the CDM applies a risk management framework based on the components (i) Selection and characterisation of the geological storage site, (ii) Risk and safety assessment, Monitoring requirements, and (iv) clearly defined distribution of liability between project participants and host country (including its transfer between the two) (UNFCCC, 2012; Dixon, Leamon, Zakkour, & Warren, 2013). To address non-permanence, the CDM offers two distinct approaches to choose from: For A/R project activities, **temporary crediting** (where removal credits are valid for a specified duration) and **long-term crediting** with required repurchase.

Puro is the only program among the compared crediting programs to also use mechanisms like **discounting the time horizon** and **easement**. The use of these mechanisms is specific to the methodology. For instance, the discounting of the time horizon is applied in the accounting of biochar carbon removal. In the Terrestrial Storage of Biomass methodology, easement is employed as a durability mechanism, which includes preventative risk mitigation through a 100-year land title with an appropriate easement.[22]

9.1.3 Reversal management mechanisms

Where carbon removal projects have a reversibility risk, comprehensive risk mitigation and mechanisms to compensate for any reversals need to be in place. Carbon crediting programmes often incorporate **buffer provisions**, which mandate that all projects facing the risk of reversibility allocate a specific percentage of credits to a buffer or insurance pool. In case of an unforeseen reversal in carbon removals, such as those resulting from incidents like fires or disease outbreaks, the buffer credits would serve as a safety net to mitigate the losses.

All five analysed programmes have provisions for buffers in place. Therefore, they deal with non-permanence risks by making use of buffer accounts. The approach to allocating a portion of a project’s carbon credits to a buffer account differs among the crediting programmes. It is either a **pre-defined percentage**, or a percentage which depends on the **risk assessment**. Pre-defined percentages may also be subject to adjustments depending on the results of the risk assessment. Puro’s buffer pool is **10%** (unless otherwise specified), ACR geological sequestration projects’ buffer pool is also **10%**, and Gold Standard applies **20%** to land use and forest projects. The CDM includes

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[22] A legal agreement between the landowner and relevant entity establishing the right to use the land for woody biomass burial, so that the carbon storage is not disturbed for a period of no less than 100 years. The easement remains on the land even when it changes ownership. This does not exclude the use of the site above the burial chamber for a non-competing use such as re-vegetation or recreation facilities which will not compromise the storage integrity of the underlying burial chambers.

provisions specifically for CCS activities, requiring that a 'reserve account' be established in the CDM registry for each CCS project, into which 5% of issued Certified Emission Reductions will be withheld (i.e., a "buffer account") (Dixon, Leamon, Zakkour, & Warren, 2013).

Verra and ACR buffer pool percentages for AFOLU projects are **risk based**. Verra provides dedicated tools for assessing the risk of reversals to determine the number of credits to be deposited in pooled buffer accounts, e.g., the AFOLU Non-Permanence Risk Tool (NPRT) and the GCS NPRT.[23]

Verra maintains separate pooled buffer accounts for AFOLU and GCS projects. In contrast, the Gold Standard operates with a single Gold Standard Buffer account specifically for Land Use and Forest activity projects. ACR, on the other hand, aggregates buffer contributions from all AFOLU carbon projects registered with ACR into one or more co-mingled accounts.

Most of the compared programs use both buffer pools and **required compensation** as reversal management mechanisms. Required compensation is a common approach employed by all the analysed crediting programs. It involves replenishing carbon credits from the buffer pool, a feature incorporated by those programs with buffer provisions, where applicable.

However, it's important to note that the CDM's required compensation for A/R activities differs from the others, as it is based on a **repurchasing requirement**, without the use of buffer pools.

In addition to the reversal management mechanisms mentioned above, ACR also employs **insurance** and other **unspecified risk mitigation mechanisms**, subject to ACR approval.

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[23] Under the CCS+ Initiative (which uses Verra standard), NPRT must also be used for Geologic Carbon Storage. The CCS+ Initiative is not a carbon crediting programme, but an initiative to come up with a comprehensive framework to cover a broad range of technologies and solutions in a modular manner. The toolkit is made accessible for voluntary and compliance standards. https://ccsplus.org/.

9.2 Leakage provisions in existing carbon crediting programmes

It is essential to include leakage emissions in the calculations to accurately measure the net emissions reductions achieved by a carbon removal project. **All** analysed programmes have carbon leakage provisions for **assessment, quantification, and deduction** of carbon leakage emissions to determine the **net impact on emissions**. Notably, Verra, Gold Standard, ACR, and CDM offer distinct modules, tools, or formulas for accounting for carbon leakage.

The management, quantification, and accounting for leakage vary depending on the nature of the activity and the carbon crediting programme under which it is registered. All the analysed carbon crediting programmes incorporate systems for **monitoring and addressing** leakage. However, these programmes differ in their approaches to mitigating leakage, with some offering different mitigation activities for leakage while others offer only quantification and deduction.

Leakage mitigation activities for Verra are detailed in the Verra Standard and are tailored to the specific methodology used. For example, Verra's AFOLU projects are encouraged to incorporate leakage management zones as part of their project design. Similarly, the Gold Standard, and ACR each adopt methodology-specific approaches. Under the CDM, A/R project activities must **be designed to minimise** carbon leakage. Furthermore, a periodic review of activities and measures aimed at minimising leakage is implemented.

9.3 Durability and leakage provisions in notable upcoming carbon crediting standards

9.3.1 European Union Carbon Removal Certification Framework

The European Commission published a proposal for the Carbon Removal Certification Framework (CRCF) in November 2022 (European Commission, 2022). The proposal sets out a general legislative framework that establishes (1) the quality criteria for carbon removals in the EU, (2) the rules for the certification of carbon removals, and (3) the rules for the functioning and recognition of the certification schemes by the European Commission. All in all, the goal is to facilitate the deployment of carbon removals in the EU.

The scope is limited to carbon removal activities within the EU (which differs from the existing standards analysed in this report that all have global scope), and the use of the framework is voluntary. The carbon removal activities are divided into three types: permanent carbon storage, carbon farming, and carbon storage in products.

The validity of the certified carbon removals is suggested to depend on the expected durability of the storage and the different risks of reversal (natural or anthropogenic) associated with the given carbon removal activity. Activities that store carbon in geological formations are deemed to provide enough certainties on the very long-term duration of several centuries for the stored carbon and are therefore suggested to be considered as providing permanent storage of carbon. Carbon farming or carbon storage in products are deemed to be more exposed to the risk of voluntary or involuntary release of carbon into the atmosphere. To account for this risk, the validity of the certified carbon removals generated by carbon farming and carbon storage in products is proposed to be subject to an expiry date matching with the end of the relevant monitoring period. The proposal suggests assuming the carbon to be released into the atmosphere thereafter unless the economic operator proves the maintenance of the carbon storage through uninterrupted monitoring activities.

The proposal also lists liability mechanisms to be introduced to address reversal. Such mechanisms could include, e.g., discounting of carbon removal units, collective buffers or accounts of carbon removal units, and up-front insurance mechanisms. As an EU-specific element, since liability mechanisms in respect of geological storage and (physical) CO_2 leakage[24], and relevant corrective measures have already been laid down by the EU ETS Directive 2003/87/EC and the CCS Directive 2009/31/EC, those liability mechanisms and corrective measures should apply to avoid double regulation.

The proposal does not offer much detail on carbon leakage. The concept only features in one of the recitals that stipulates "*In the case of carbon farming, the carbon captured by an afforestation activity or the carbon kept in the ground by a peatland*

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[24] Leakage in the CCS Directive 2009/31/EC is defined as „*any release of CO2 from the storage complex*". In the current report, the term „reversal" is used to describe such incident

rewetting activity should outweigh the emissions from the machinery used to carry out the carbon removal activity or the indirect land use change emissions that can be caused by carbon leakage" (European Commission, 2022).

Approving the final legislative text of the CRCF estimated in Q1 2024, will be the first step and won't answer detailed questions on reversals and leakage. Compared to the proposal, additional details might appear in the final version of the framework during the interinstitutional negotiations. Both the European Parliament[25] and the Council of the EU[26] have finished deliberations on their respective changes to the proposal. Other elements will be tackled when detailed certification methodologies are developed. During this process, "*specific rules will be tailored to the characteristics of the different types of carbon removal activities: for instance, the rules will recognise the strong guarantees for permanence offered by solutions storing carbon in geological formations, while clarifying minimum sustainability requirements for carbon farming activities*" (European Commission, 2022). The European Commission will develop these methodologies in close consultation with the Expert Group on Carbon Removals.[27]

9.3.2 Paris Agreement Article 6.4 Mechanism

The Article 6.4 Supervisory Body (SB) developed recommendations that include sections on durability and avoidance of leakage as part of the general framework of the crediting mechanism. These recommendations are up for adoption at the CMA5 during the COP28.

Reversal Management

The rules on addressing reversals from carbon removal activities are stipulated in the recommendation on activities involving removals (UNFCCC, 2023).

The risk of reversals must be minimised and reversals have to be addressed in full. Reversal risk assessment divides risk types into avoidable and unavoidable, and requires activity-level risk assessment to be conducted using robust methods to identify and assess the reversal risks, including to quantify and score them, for instance, the nature, scale, likelihood, and duration of the risks and of potential

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[25] https://www.europarl.europa.eu/news/en/press-room/20231117IPR12212/carbon-removals-parliament-wants-eu-certification-scheme-to-boost-uptake

[26] https://www.consilium.europa.eu/en/press/press-releases/2023/11/17/climate-neutrality-council-ready-to-start-talks-with-parliament-on-eu-carbon-removals-certification-framework/

[27] https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/expert-group-carbon-removals_en

reversals. A plan to mitigate and monitor the risks must be developed, and risks that cannot be eliminated have to be addressed.

Risk assessment has to be reviewed and revised every five years from the start of the first crediting period. The SB will develop a risk assessment (and reversal notification) tool and further details will be included there. The Supervisory Body will develop further guidance on avoidable and unavoidable reversals, including how they are distinguished and demonstrated.

Reversal management mechanisms include (i) Reversal Risk Buffer Pool established by the Supervisory Body and (ii) direct cancellation of A6.4ERs. Buffer pool is to be used for unavoidable reversals. Avoidable reversals and reversals from activities with negligible reversal risk that forego the use of the buffer pool are to be addressed by cancellation of an equivalent amount of 6.4 ERs from other 6.4 activities.

Carbon Leakage Provisions

The rules on leakage are included in the recommendation on requirements for the development and assessment of mechanism methodologies[28] and require the identification of potential sources of leakage, and avoidance of and minimisation of leakage. The SB will develop a methodological tool for this.

According to the provisions, leakage may be avoided, minimised, or addressed by (inter alia) discounting credited volumes, scrapping of baseline equipment, application of higher-level elements (e g. standardised baselines at a higher level of aggregation), nesting (aligning relevant aspects with an existing higher-level crediting programme), and by upscaling implementation (implementing activities on sectoral, sub-national or national level). For some types of activities, monitoring at jurisdictional level and use of standardised baselines (or equivalent) is necessary to quantify and account for leakage.

The recommendations by the Article 6.4 SB establishing specific accounting rules may differ from similar criteria being applied by other policy makers, e.g., through the EU CRCF. Elkerbout & Bryhn (2022) argue that barriers to international cooperation are likely to emerge as project developers will need to deal with multiple rulebooks.

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[28] https://unfccc.int/sites/default/files/resource/a64-sb009-a01.pdf

9.4 Consideration of risk of reversal, leakage and monitoring in the context of removals guidance

9.4.1 Risk of reversal

Supplier Obligations

Supplier obligations could involve requirements to renew credits on a defined schedule or whenever monitoring identifies a reversal. Challenges arise when the original developer ceases to exist or lacks incentives to replace reversed carbon far in the future. Supplier obligations are normally timebound, lasting for a contracted period.

A main pathway for suppliers to ensure durability is physical buffer pools, involving the setting aside of a reserve of carbon credits that can be used to replace reversed temporary storage as outlined in section 9.1.3. The size of the physical buffer pool needs to be large enough to address realistic reversal scenarios across all the projects contributing credits. This model avoids complex calculations of reversal risks and premiums. However, estimating the adequate pool size can still be challenging, and the replacement credits face the same reversal risks as those they are meant to replace. Strong governance and ongoing contributions are needed to maintain the buffer pool's ability to address reversals over long time periods.

Buyer obligations

Buyer obligations to replace any reversed carbon could involve requirements to re-purchase new credits periodically as the original ones expire (Galinato, Olanie, Uchida, & Yoder, 2011), either after a contracted time period, or assuming the responsibility directly after carbon credits are purchased. Buyers could pay ex-ante into pooled funds that are used to replace reversed carbon from projects they supported. Insurance-style models would also work, where buyers pay ongoing premiums and reversed carbon is replaced using these pooled funds. The amount paid could be proportional to the risk and size of their temporary storage carbon credit portfolio.

Challenges arise in accurately pricing risk over long periods and ensuring that funds are still available when replacement is needed. Buyers obligated to re-purchase credits also face risks of rises in the future price of carbon credits. Buyers may also resist taking on open-ended future liabilities.

If the buyer is a company, one option is to shift the replacement obligation to the government entity where the temporary storage project took place after a set period of time, such as 20 or 30 years. This spreads the responsibility across society and avoids reliance on a single private entity. However, it would require public funds and governance to fulfil this obligation long-term.

Applying the like-for-like principle

The most stringent approach for managing risk of reversal, temporary credits, did not work under the CDM as demand was lacking. Voluntary markets have generally applied buffer reserves at varying percentages. However, it remains unclear how MRV and buffer administration can be ensured over many decades or beyond a century by private actors, given that their average lifespan is much lower. It is reasonable to conclude that there is no overall convincing solution in sight (Michaelowa, et al., 2023).

Alternatively, demand for carbon removal credits with different risks of reversal can be tied to why the removal is used. There are several main use cases of carbon removal, which, as explained below, have very different implications on what types of removals could be accepted and how reversals would need to be treated.

Offset a specific CO_2 emission to avoid increased warming: This use case involves using carbon removal to directly neutralise or offset a tonne of CO_2 released from a specific source and prevent that emission from increasing atmospheric CO_2 levels. In this case, to have an equivalent climate impact, the carbon removal must have a durability that matches the lifetime of the emission (the "like for like" removal principle). In the case of CO_2, the removal would need to be very long lived or permanent. If temporary or vulnerable storage were used, the removal would fail to prevent the warming from the original emission in the case of reversal. If temporary or vulnerable storage are used, the renewal mechanism must be iron-clad, something that could be difficult to ensure. Durable storage lasting hundreds of years could potentially be used since it helps push peak warming forward, and buys time, something storage being re-released before peak temperatures do not. If non-permanent, but long-lasting storage shall be allowed is a policy choice.

Continuously offset short-lived climate pollutants to lower warming: Carbon removal could be used to continuously offset ongoing methane or HFC emissions. Here the storage does not need to be permanent since the lifetime of the GHG being offset is short.

Address historical CO_2 emissions or, contribute to more CO_2 being taken out of the atmosphere without tying it to a certain emission to offset: Carbon removal could also be used to take CO_2 out of the atmosphere without linking it to a specific emission to offset. This could be a pure contribution to achieving global climate targets, or to address the buyers' historical emissions. In this case, the climate impact relies on the cumulative amount and duration of storage. Permanent storage is ideal to maximize climate benefit, but storage with a more significant risk of reversal can potentially also be used given that sufficiently robust provisions are applied to ensure replacement upon reversal. Here a cost-benefit optimization can be used to determine the optimal use of removals.

9.4.2 Addressing leakage

Meyfroidt, et al. (2020) make a number of general observations on the basis of extensive literature review:

- A proper accounting of spillover and leakage effects requires accounting for effects across sectors and activities, e.g., across supply chains, the whole agricultural or food system, across food and non-food sectors, or across land and non-land related sources of GHG emissions.
- The causal attribution of observed spillover to a given intervention remains difficult, because the signal of the intervention mixes with the multiple drivers of land use change, including changes in local and global markets, technologies, and other policies, and because multiple mechanisms overlap on the same land.
- While land use impacts can be difficult to attribute to a specific policy ex-post, identifying the conditions that make places and actors more susceptible to leakage can help improve the design of policies. In this regard, *conditions that make places more likely to generate land use leakage* include high labour and capital mobility, lack of knowledge or technology for agricultural intensification combined with elastic domestic or international demand. Supply-chain leakage is more likely in a diffuse purchasing market that exhibits heterogeneous preferences for sustainably-sourced

> products. It is also more likely when commodities are fungible and have complex production life cycles, which complicates traceability. Conditions that make places *more susceptible to absorb leakage* includes (i) being susceptible to respond to market signals because of available, suitable and accessible land and other resources, and being prone to respond by land use expansion on environmentally valuable land, in particular because of inadequate environmental governance, including less stringent land use restrictions and (ii) connectivity to the place where an intervention occurs.

Filewood and McCarney (2023) present evidence that leakage is vastly underestimated in practice and argue that current efforts to improve accounting methods are unlikely to deliver the accuracy required. Noting that while activity leakage may be tractable (targeted agents are known, and their actions are observable), market leakage is not, the authors propose and elaborate an alternative approach to address leakage by design. The approach includes one principle which fundamentally addresses a necessary design feature to control market leakage at the level of an individual project issuing carbon credits:

- When the design of a nature-based intervention implies market leakage risks, upper-bound estimates of potential leakage should be used.

The second principle takes note of that substituting uncertain carbon credits for certain emissions reductions risks decoupling measured progress toward policy targets from physical changes in stocks of atmospheric GHG, and therefore provides a critical demand-side safeguard for compliance carbon markets:

- Nature-based credits which include market leakage risk in their design should not substitute for avoided emissions in compliance settings.

9.4.3 Monitoring

Monitoring, reporting and verification (MRV) is important from both a carbon accounting and a GHG liability perspective. It will therefore be necessary to develop the ability to adequately audit the quantity of CO_2 removed by a given CDR method at a given time. Concluding monitoring is an integral part of completing a CDR project. CDR methods vary significantly in terms of ability to monitor, which comprises accuracy and precision of monitoring, the cost and frequency of monitoring to verify quantity of CO_2 stored (BEIS, 2021). Thus, individual MRV protocols will be specific to CDR methods and to some extent also context.

Smith et al. (2023) qualitatively assessed feasibility of MRV for the capture and storage steps of CDR methods, scoring the simplicity/precision of quantifying the amount of carbon removed (low/med/high/v high) and the existence or not of an MRV methodology in the IPCC Guidelines for National Greenhouse Gas Inventories. The result of the assessment is reflected in **Error! Reference source not found.**.

Table 5. Feasibility of MRV for CDR methods, per respective capture and storage processes. Source: Smith et al. (2023).

CDR method	Capture		Storage	
	Simplicity/precision of quantification	IPCC MRV methodology	Simplicity/precision of quantification	IPCC MRV methodology
Afforestation/ Reforestation	High	Yes	High	Yes
Agroforestry and improved forest management	Medium	Yes	Medium	Yes
Durable Harvested Wood Products	High	Yes	Medium	Yes
Soil carbon sequestration	Medium	Yes	Low	Yes
Biochar	High	Yes	Medium	Yes
BECCS (Bioenergy with Carbon Capture and Storage)	High	Yes	High	Yes
DACCS (Direct Air Carbon Capture and Storage)	Very high	No	High	Yes
Enhanced rock weathering	Low	No	Low	No
Peatland and wetland restoration	Low	Yes	Low	Yes
Coastal wetland (blue carbon) management	Low	No	Medium	No
Ocean alkalininity enhancement	Low	No	Low	No
Ocean fertilisation	Low	No	Low	No

Table 6 summarises key considerations in relation to measurability and verifiability of CDR methods, including the occurrence of existing project certification methodologies (Umweltbundesamt, 2021; BEIS, 2021; Ho, et al., 2023; NASEM, 2022). MRV rules already exist for most conventional NbS at national level through the IPCC Guidelines for National Greenhouse Gas Inventories and at project-level with a large base of existing methodologies within carbon crediting programmes.[29] Conventional NbS are, therefore, excluded from the table with the exception of soil carbon sequestration.

Table 6: Measurability and verifiability of CDR methods (excluding conventional NbS). Sources: Umveltbundesamt (2021), BEIS (2021), Ho et al. (2023), NASEM (2022).

CDR method	
Durable Harvested Wood Products	The IPCC Guidelines for National Greenhouse Gas Inventories set accounting approaches Carbon removals from biomass in buildings connected to biogenic storage function of harvested wood products. The IPCC Guidelines lists different approaches which treat differently the long-term biogenic carbon storage function of wood products. Emissions and removals resulting from changes in the pool of harvested wood products (paper, wood panels and sawn wood) can be estimated using the first order decay function and specific default half-life values (25 years for wood panels and 35 years for sawn wood.
Soil carbon sequestration	Monitoring of the soil organic carbon (SOC) can be either 1) predicted via empirical / process models, or 2) measured via soil sampling. The monitoring of SOC via sampling at field level is very costly due to inherent heterogeneity at each field. There is also uncertainty associated with modelling / upscaling carbon sequestration rates from long-term agricultural experiments. In estimating SOC levels via modelling, sources of uncertainties are cumulative, need to be identified, and uncertainties estimated in quantitative terms. Uncertainties, for example, relate to: limited understanding of factors that influence SOC quantity and stability, time of sampling, sampling depth, processing of data, assumptions and input data in modelling of SOC stock changes, lack of data on current / existing levels of SOC. New technological developments are emerging that have potential to reduce costs of MRV and increase certainty in assessments.
Biochar	Effective monitoring at project-level of GHG emissions across value chain including feedstock production is required. Emissions from bioenergy production vary between geographies, feedstocks, and timeframe. Consequently, these variables represent significant challenges for measurability and verifiability. The biochar production process is quite well understood. Biochar properties depend on a combination of nature of feedstock and parameters in the pyrolysis or gasification process. Carbon yield in biochar production by pyrolysis or gasification can vary between 10-50%. Carbon content of biochar can be measured by reliable methods.

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[29] However, uncertainty of measurements, additionality and baseline emissions are challenging for NBS.

	Re-release of CO_2 will occur associated with the application and incorporation of biochar into a given tract of land. The 2019 revision of the 2006 IPCC guidelines included a specific annex focused on estimating biochar impacts on soil carbon. The annex provides a basis for developing a tier 1 methodology in the future. It is a top-down method consisting of two key calculation elements: 1) organic carbon content factor of biochar and 2) the fraction of biochar remaining after 100 years, which the method proposes depends only on the temperature of pyrolysis.
BECCS (Bioenergy with Carbon Capture and Storage)	CO_2 captured is directly measurable, any fossil emissions (co-firing) can be estimated through mass balance calculations, and energy penalties are easily traceable. Effective monitoring at project-level of GHG emissions across value chain including feedstock production is required. Emissions from bioenergy production vary between geographies, feedstocks, and timeframe. Consequently, these variables represent significant challenges for measurability and verifiability. The integrity of the CO_2 store can be expected to be robustly demonstrated via store appraisal. On injection, the CO_2 plume can be monitored via a combination of 3D seismic surveys, seabed gravimetric monitoring, and mathematical modelling. Once the CO_2 plume is observed to be moving in line with model predictions, efforts towards project completion can begin. An ISO standard for geological CO_2 storage has been developed. There is a current lack of MRV guidelines for carbon mineralisation specifically. Carbon mineralisation may not require long-term monitoring (in comparison with conventional geological storage).
DACCS (Direct Air Carbon Capture and Storage)	CO_2 captured is directly measurable and energy usage easily traceable. For MRV information reg. CO_2 storage, see BECCS.
Enhanced rock weathering	Methodological uncertainties and high complexity related to monitoring, reporting and verification. Audited field scale assessments including environmental monitoring as well as evaluation of the efficacy of CO_2 capture are required. It will be necessary to develop a minerology baseline. In addition, owing to natural heterogeneity, sampling (using geostatistical methods) of the prepared material will likely be essential. As the carbonation reaction progresses, periodic sampling of the reacted material is likely to be required. Not included in any carbon accounting agreements (e.g. not included in IPCC Guidelines for National Greenhouse Gas Inventories).
Ocean alkalinity enhancement	Due to turbulence in oceans and since reaching equilibration between the ocean and atmosphere can take several months or longer, added alkalinity will be diluted to perturbation levels undetectable above background variability on timescales relevant for MRV. Therefore, comprehensive quantification of carbon removal via ocean alkalinity enhancement will be impossible through observational methods alone and numerical simulations will be required.

	Ocean alkalinity enhancement modelling experiments coupled with field trials will be necessary to identify the long-term approach to robust MRV. Ultimately it will be desirable to develop approaches to MRV that can be accomplished at a reduced computational cost.
Ocean fertilisation	Quantification and monitoring are likely to be challenging, especially due to the large areas involved, long supply chains for fertilizing materials, use of seagoing vessels, effects of ocean circulation, and overall biogeochemical complexity of the ocean.

10 Carbon Removal Obligations (CROs)

An array of regulatory instruments has been proposed to fund CDR initiatives and encourage their widespread adoption (e.g., Hickey et al., 2023; Zetterberg et al., 2021). These instruments encompass various approaches, including direct subsidies, quota obligations mandating emitting sectors to procure removal credits, carbon take-back obligations (CTBOs), integration of CDR into cap-and-trade schemes or carbon tax systems, and, more generally, participation in carbon markets (both compliance and voluntary). These mechanisms primarily focus on financing CDR activities contemporaneously, meaning that – in one way or another – emitters pay for CDR efforts occurring at the same time as their emissions, and which compensate a fraction thereof.

This approach is viable as long as removals are smaller than or equal to gross CO_2 emissions, hence, until emissions reach net-zero. Beyond this point, when removals begin to exceed residual emissions – a highly likely necessity to meet the temperature goals outlined in the Paris Agreement – these mechanisms will lead to a funding gap. This gap might need to be filled by public funds, potentially placing an additional financial burden on taxpayers. This burden could compound existing financial commitments needed for adaptation measures and addressing loss and damage. To establish a consistent and sustainable funding mechanism for CDR that extends beyond the net-zero phase, it is imperative to recognize that every emission made after the depletion of the global carbon budget, will necessitate an equivalent amount of carbon removal at a later point in time.

Carbon Removal Obligations (CROs) offer a novel approach in addressing climate change challenges (Bednar J. , et al., 2021). Fundamentally, CROs are legal mandates directed at emitters. They stipulate that for every tonne of "carbon debt" released into the atmosphere, an equivalent amount of CO_2 must be removed by a predetermined maturity of the CRO. Such removal can be facilitated through mechanisms like the acquisition of a removal unit from a carbon removals market. The implementation of CROs induces a dual demand – for carbon removal and emission reductions. Thus, emission reductions do not inherently require a distinct market structure, CROs induce a shadow price for emission reductions through their design.

A distinct aspect of the CRO framework is its focus on "carbon debt", which denotes every tonne of gross CO_2 emissions surpassing the remaining carbon budget. The global carbon budget for a 1.5°C target is projected to be depleted in less than a decade (Lamboll, et al., 2023). Moreover, when considering the historical emissions of industrial nations, regions such as the EU or North America may have already surpassed their respective carbon budgets. This underscores the immediate importance of CROs, rather than being a consideration for the future.

In the discourse surrounding CROs, the term "temporary atmospheric carbon storage" gains importance. This refers to the interval between CO_2 emissions and their subsequent removal. While discussions in climate policy frequently emphasize the temporary storage capacity of specific NbS, CROs draw a parallel between these solutions and the atmosphere's capacity for temporary CO_2 storage. Estimating the cost associated with such storage is complex, given that it is influenced by Earth system dynamics, the costs of climate impacts, and the specific properties of abatement options – including their associated costs, potential side-effects, and other relevant characteristics. However, with the application of integrated and risk-robust methodologies, a comprehensive cost assessment is attainable.

10.1 Pricing of atmospheric CO_2 storage

From an economic perspective, CROs can be analogized to interest-bearing financial instruments (Bednar, et al., 2023). Essentially, utilizing a portion of the atmosphere's storage capacity is economically viewed as incurring a debt, and similar to financial systems, this debt accrues interest over time. This interest-based pricing mechanism serves several objectives:

First, it not only moderates the demand for CROs (and thus for CDR) but also tunes the price trajectory of CDR and the shadow price of ERs (Bednar, Baklanov, & Macinante, 2023). By concurrently adjusting these price levels, it offers distinct control over emission and removal pathways. This ensures, as presented in the Proactive Transition Scenario of section 7.2, that carbon removal mechanisms augment emission reduction initiatives without undermining them, thus, minimizing both deterrence of decarbonization as well as the overshoot (see also section 7.6).

Second, this pricing framework serves as a financial safeguard, similar to the way interest rates on bank loans are set to reflect the borrower's financial risk and mitigate potential defaults. By employing a structure reminiscent of private borrowing, the framework ensures emitters remain accountable and financially committed to future carbon removals.

Third, considering the quantifiable relationship between temporary atmospheric CO_2 storage and resulting climate impacts, the revenue generated from CROs assumes a significant role. A strategic allocation of these funds can address issues of intergenerational equity, directing resources to mitigation and adaptation needs in regions and communities bearing the brunt of climate change impacts.

For the corporate sector, CROs signify an alignment of regulatory adherence with business operations. By embedding climate mitigation strategies within core economic activities, they ensure that the externalities of carbon emissions are addressed at their roots. This integration offers businesses a consistent trajectory for planning, insulating them from political risks. CROs, thus, facilitate a proactive business approach, prompting innovations in emission reductions and CDR methods. Moreover, the flexibility inherent in CROs allows for an alignment between decarbonization strategies and capital renewal cycles.

11 Recommendations

The present climate policy and actual decision-making are still centred on achieving net-zero carbon emissions predictably leading to a massive overshoot. However, there is a lack of plans to reverse legacy emissions to ensure that the increase in global temperatures does not exceed 1.5°C in the long run. Even with immediate global action to cut emissions, the 1.5°C limit would likely be surpassed just over ten years from now or sooner. In the short to medium term, removing CO_2 from the atmosphere (Carbon Dioxide Removal – CDR -, henceforth “carbon removal”) is vital for minimizing overshoot and avert potential Earth system tipping points, aiming for net-zero carbon emissions by mid-century. The long-term challenge is the inevitable reversal of the overshoot, requiring carbon removal to outpace residual emissions, leading to net negative emissions globally. This involves extracting more CO_2 from the atmosphere than is emitted, potentially cooling the planet and achieving the 1.5°C goal by 2100, even with a temporary overshoot.

Responsibility for climate overshoot reversal must be given immediate attention in the climate talks as the sum of climate pledges will create a sizeable overshoot. A well-structured governance system regulating the implementation of a politically negotiated burden-sharing arrangement is needed to guarantee the viability of a global net-negative GHG economy to emerge within the next three decades.

Addressing financial constraints and ensuring fairness across generations is essential, acknowledging that carbon debt and overshoot commitments begin with every emission today. Thus, plans to manage the overshoot should start soon, certainly before the carbon budget is depleted in the upcoming decade. This involves extensive carbon removal throughout the century, sharply contrasting with the current net-zero focused policy. To genuinely prevent an overshoot, both aggressive emission reductions and large-scale deployment of a range of CDR methods – to accomplish massive carbon removal – are necessary. Vital questions about overshoot management, its timing, responsibility, financing, and impacts need answers through a well-designed policy framework like a Carbon Removal Obligation (CRO).

This report identifies, and stresses the importance of addressing, two fundamental risks that come inherently with the inclusion of carbon removal among GHG mitigation options. *Firstly*, the availability of carbon removal may divert focus away from deep and rapid emission cuts. It is imperative to manage the risk of less emphasis on fossil fuel mitigation due to the availability of carbon removal (known as "mitigation deterrence") both in terms of concurrent action ("contemporaneous substitution") and through the postponement of near-term emission reductions due to the prospect of future low-cost, high potential carbon removal ("intertemporal substitution"). *Secondly*, carbon removal is associated with the risk that carbon removed from the atmosphere might be re-released. When CDR methods are deployed, the sequestered carbon needs to be stored or utilized in a way that ensures it remains out of the atmosphere for a significant period. Addressing the risk of reversal of carbon storage is critical for the effectiveness of mitigation strategies in achieving long-term climate goals. In particular carbon sequestered through many so-called Nature-based Solutions (NbS), such as reforestation or wetland restoration, is susceptible to reversal due to both natural disturbances and human activities. Properly designing and implementing carbon removal activities, ensuring reliable storage mechanisms, and considering long-term risks are essential steps to minimize the risk of carbon being re-released into the atmosphere after removal.

Mitigation policies must build on separate short- and long-term targets for emission reductions and carbon removal to contain the risk of mitigation deterrence. Such a separate targets strategy should consider a near-term overshoot target that incorporates early and radical emission reductions with simultaneous near-term development and ramping-up of CDR methods to clarify their actual potentials and the scaling properties of specific technological options. In the medium-term perspective, a policy design that separates the promotion of large-scale deployment of carbon removal technologies from emission reduction policies will ensure that reductions of abatable emissions are complemented and not crowded out by CDR. By advocating for the early integration of CDR (which would benefit also from a more general development of Carbon Capture and Storage), technological learning is enhanced, and economies of scale are realized, allowing for a gradual decline in cost over time. This is vital to reduce the extent of the overshoot and its inherent risks as well as to achieve net-zero timely.

Ecosystem management complemented with novel biomass-based CDR methods characterised by durable storage, such as biochar carbon removal, and bioenergy with carbon capture and storage, typically outperform strategies based purely on NbS. While natural ecosystems like forests capture carbon, saturation is reached and their efficiency declines over time due to factors such as tree senescence, decay and disturbances. In contrast, combining forest management with novel biomass-based CDR methods can maximize carbon sequestration by both rejuvenating forests and preventing biomass decay.

Policies for the promotion of carbon removals should incorporate risk-mitigation strategies aiming at the long-term goal of ensuring permanence by combining NbS with novel biomass-based CDR methods.

This report concludes that durability and reversal management mechanisms of existing carbon crediting programmes, and considered in current policy processes, are in principle applicable to all CDR methods. However, there is no overall convincing solution in sight. In terms of risk management in relation to durability constraints, durability and reversal management mechanisms should be complemented by provisions related to for what purposes carbon credits are allowed to be used.

Policies must be designed to limit the fungibility between emission reduction and carbon removal mitigation outcomes in emissions trading. This should include provisions that limit the extent to which carbon removals that do not have very long-lived or permanent storage are allowed to be used for offsetting fossil CO_2 emissions.

In the context of carbon removal, so-called carbon leakage implies significant integrity risks in relation to land use-related activities. Leakage can be separated into two types: ‘’direct’’ (or “activity”) leakage and ‘’market’’ leakage. Direct leakage arises when the economic agents targeted by an intervention shift activities outside of the accounting boundary, whereas market leakage arises when non-targeted agents adjust their behaviour in response to altered economic incentives. Evidence is emerging that leakage is vastly underestimated in practice.

Removals guidance must take into account that while direct leakage may be tractable, detecting and quantifying market leakage faces severe challenges. Unless more robust carbon leakage accounting methods are developed, it is therefore recommended that: When the design of nature-based carbon removal interventions implies market leakage risks, upper-bound estimates of potential leakage should be used. Furthermore, nature-based credits which include market leakage risk in their design should not substitute for emission reductions in compliance settings.

CDR methods vary significantly in terms of ability to monitor, which comprises accuracy and precision of monitoring, as well as the cost and frequency of monitoring to verify the quantity of carbon stored.

Monitoring, Reporting, and Verification (MRV) protocols should consider the feasibility of MRV for the capture and storage steps of CDR methods separately. MRV protocols will be *specific to individual CDR methods and to some extent also context. Some novel CDR methods need much further development before robust MRV can be applied with respect to mitigation outcome and in some cases potential side effects. This implies restrictions concerning their use for offsetting.*

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Appendix 1

Table 7: Mapping of durability provisions for carbon removal in five carbon crediting programmes (this data is as of 1 Oct 2023).

	Verra	Gold Standard	ACR	CDM	Puro
Governance level	**Non-profit corporation**.[30]	**Non-profit organisation**.[33]	**Non-profit enterprise**.[37]	**Project-based flexible mechanism under the UNFCCC**. [40]	**For-profit organisation**, a B2B marketplace, standard, and registry.
Organisation, accreditations, endorsements	The Verified Carbon Standard (VCS) Program is managed by Verra with the support of Verra's Board members, staff, advisory groups and committees, and stakeholder input collected through engagement.[31]	Gold Standard's day-to-day activities are run by the Secretariat and overseen by the Governance Board who provide financial oversight and strategic governance. Technical Advisory Committee is responsible for ensuring the rigor and integrity in all of their work, proven	Direct oversight of ACR program is provided by the Winrock International Management and Executive Teams, as well as the Winrock International Board of Directors. Technical decisions are made by sector-specific Technical Committees who review new methodologies and tools, advise the	The *CDM Executive Board* (CDM EB) supervises the Kyoto Protocol's clean development mechanism under the authority and guidance of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol.[41]	Puro Standard General Rules are governed by the independent external Advisory Board. Methodologies are co-created with experts and Board of Directors oversees business operations.[43]

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[30] https://verra.org/about/overview/
[31] https://verra.org/programs/verified-carbon-standard/governance-development/
[33] https://www.goldstandard.org/about-us/governance
[37] https://americancarbonregistry.org/
[40] https://cdm.unfccc.int/about/index.html
[41] https://cdm.unfccc.int/EB/index.html
[43] https://puro.earth/puro-standard-carbon-removal-credits/ and https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/General%20Rules/Puro%20Rules%20v3.0.pdf

	ICROA endorsement.[32]	existing programs and innovative new initiatives.[34] ISEAL code compliant.[35] ICROA endorsement.[36]	selection of scientific peer reviewers, and advise ACR on the need to update standards and commission new methodologies or tools.[38] ICROA endorsement.[39]	ICROA endorsement.[42]	ICROA endorsement.[44]
Scope and Eligibility	Reductions and **removals,** including jurisdictional programs and nested REDD+. Geographical scope: global	Reductions and **Land Use and Forests and CDR**. The eligibility of CDR project is subject to	Reductions and **removals**. **AFOLU** and **geologic sequestration**. Geographical scope: global	Reductions and **removals**. **Afforestation** and **Reforestation**, **CCS**. Geographical scope: global	Sole focus on **carbon removal**. **Biochar, Carbonated Materials, Geologically Stored Carbon, Enhanced Rock Weathering**, and **Terrestrial Storage of Biomass**.[46] Geographical scope: global

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[32] https://icroa.org/standard-endorsement/

[34] https://goldstandardhelp.freshdesk.com/support/solutions/articles/44001989663-how-is-gold-standard-governed-

[35] https://www.isealalliance.org/community-members/gold-standard

[36] https://icroa.org/standard-endorsement/

[38] https://acrcarbon.org/about-us/ and https://www.offsetguide.org/understanding-carbon-offsets/carbon-offset-programs/voluntary-offset-programs/american-carbon-registry/

[39] https://icroa.org/standard-endorsement/

[42] https://icroa.org/standard-endorsement/

[44] https://icroa.org/standard-endorsement/

[46] https://puro.earth/carbon-removal-methods/

		the availability of an applicable approved Gold Standard methodology [45] Geographical scope: global			
Durability requirements	Verra AFOLU and GCS projects: **20 years** minimum, up to **100 years.**[47] All VCUs issued to AFOLU and GCS projects (as with all projects) are permanent.[48] Project crediting period lengths: 7 (twice renewable	5 (5-year renewable certification cycle), **10 fixed for AGR**, **21**, for A/R **30-50 years**[50] [51] [52]	ACR **AFOLU** minimum durability **40 years.** ACR geologic sequestration minimum durability **5 years** (after the injection period).	7, 10, **20** and **30 years**[53]	Minimum durability **100 years.**[54] 5-year crediting period; max 15-year crediting period renewable twice possible crediting period 45 years. [55]

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[45] https://globalgoals.goldstandard.org/501-pr-ghg-emissions-reductions-sequestration/ 5.1.1
[47] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf 3.9.3
[48] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf
[50] https://www.goldstandard.org/project-developers/standard-documents 5.1.1
[51] https://www.goldstandard.org/project-developers/standard-documents Product requirements 10.1.5
[52] https://globalgoals.goldstandard.org/standards/203_V1.2.1_AR_LUF-Activity-Requirements.pdf
[53] https://cdm.unfccc.int/EB/028/eb28_repan32.pdf and https://cdm.unfccc.int/Reference/COPMOP/08a01.pdf#page=6
[54] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/General%20Rules/Puro%20Rules%20v3.0.pdf
[55] https://unfccc.int/sites/default/files/resource/sb006_pubic_conslutations_removals_Puro.earth_.pdf

	for a total of up to 21), 10 fixed, except for AFOLU and GCS 20-100 years. [49]				
Durability Mechanism **– how it is guaranteed that carbon will remain stored?**	**Commitment period.**[56] AFOLU projects shall have a credible and robust plan for managing and implementing the project over the project crediting period. [57] The permanence of carbon stocks shall be monitored for	**Commitment period.** For the duration of the crediting period the project developer shall own the rights of the project area, hold all necessary permits to implement the project etc.	**Commitment period** (ACR AFOLU)[60]**; Demonstration of stability** (ACR Geo seq).[61] ACR AFOLU projects must commit to maintain, monitor, and verify project activity for a Minimum Project Term of forty (40) years.	**Temporary crediting during commitment period; Long-term crediting and Require repurchase**. Temporary crediting and long-term crediting approach to account for non-permanence.[62] Temporary credits are issued for an	**Commitment period. Discounting time horizon**[64]**; Easement**[65]**.** The CO_2 removal supplier must provide a risk assessment and mitigation plan for the risks related to the permanence of the CO_2 sequestration[66] Annual performance-monitoring during the time period when the project is operational. Monitoring,

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[49] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf 3.9

[56] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf. 3.2.12; 3.9.4

[57] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf 3.9.4

[60] https://acrcarbon.org/wp-content/uploads/2023/10/ACR-Standard-v8.0.pdf ACR Standard 8.0

[61] https://acrcarbon.org/wp-content/uploads/2023/03/ACR-CCS-v1.1.pdf 6.3

[62] https://cdm.unfccc.int/Reference/COPMOP/08a01.pdf#page=6 Annex, section K

[64] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Biochar%20Methodology.pdf 4.2

[65] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Engineered%20Biomass%20Deposits.pdf 7.1, 7.2

[66] https://unfccc.int/sites/default/files/resource/sb006_pubic_conslutations_removals_Puro.earth_.pdf

	a **minimum of 40 years.** At its discretion, Verra may agree to monitor a project or class of project types where the crediting period is less than 40 years.[58]	Buffer continues beyond the crediting period for an undefined period.[59]	Project Proponents must demonstrate that the CO_2 captured and stored is permanently sequestered underground.	afforestation or reforestation project activity since the project start date, and long-term credits are issued during the verification period.[63]	reporting, and verification (MRV) requirements are set in each methodology. [67] Easement - Land title for 100 years with an appropriate easement.[68] Discounting time-horizon - pre-issuance deduction for biochar based on degradation curves as a function of biochar quality, soil temperature and after a time period of 100 years has lapsed.[69]

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[58] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf e.g., 3.2.24
[59] https://www.goldstandard.org/our-story/sector-land-use-activities-nature-based-solutions
[63] https://cdm.unfccc.int/Reference/COPMOP/08a01.pdf#page=6 Annex
[67] https://unfccc.int/sites/default/files/resource/sb006_pubic_conslutations_removals_Puro.earth_.pdf
[68] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Engineered%20Biomass%20Deposits.pdf 7.2
[69] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Biochar%20Methodology.pdf 4.2

Reversal management mechanism **- how the SDO accounts for or remediates carbon lost from a reservoir?**	**Buffer pool; Required compensation** Buffer pool (% of credits based on risk assessment). Non-permanence risk in AFOLU and Geologic Carbon Storage (GCS) projects is addressed through the use of a project risk analysis, using the AFOLU Non-Permanence Risk Tool (NPRT) and the GCS NPRT,	**Buffer pool; Required compensation** Buffer pool (20% of credits for land use & forests projects).[71] Buffer continues beyond the crediting period for an undefined period.[72] Not required for permanent reductions or avoidance. It involves no risk of reversals.[73] Compensation of lost units [74]	**Buffer pool; Required compensation; insurance; other risk mitigation mechanisms.** ACR AFOLU – **Buffer pool** (% based on risk assessment). + Periodical analysation of reversal and **Reversal Risk Mitigation** Agreement with ACR. [75] [76] ACR geo seq – **Insurance** OR **Buffer pool 10%** OR other ACR-approved risk mitigation mechanisms. [77]	**Required compensation** (Repurchasing requirement). Long-term credits are required to be replaced in case of reversals.[79]	**Buffer pool; Required compensation.** Risk assessment. Buffer pool (10% unless otherwise specified). Activities to assess the risk of reversals occur before, during and after the operation of the project. Carbon credits are only issued after the CO_2 removal has occurred (ex-post credits).[80]

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[71] https://www.goldstandard.org/project-developers/standard-documents Product requirements 11.1
[72] https://www.goldstandard.org/our-story/sector-land-use-activities-nature-based-solutions
[73] https://globalgoals.goldstandard.org/501-pr-ghg-emissions-reductions-sequestration/ 11.1.1
[74] https://www.goldstandard.org/our-story/sector-land-use-activities-nature-based-solutions
[75] https://acrcarbon.org/wp-content/uploads/2023/10/ACR-Standard-v8.0.pdf and
[76] https://acrcarbon.org/wp-content/uploads/2021/02/ACR-Buffer-Pool-Terms-and-Conditions-Jan-2021.pdf
[77] https://acrcarbon.org/wp-content/uploads/2023/03/ACR-CCS-v1.1.pdf
[79] https://cdm.unfccc.int/Reference/COPMOP/08a01.pdf#page=6 Annex, section K, 47., 49.
[80] https://unfccc.int/sites/default/files/resource/sb006_pubic_conslutations_removals_Puro.earth_.pdf

	respectively. These tools determine the number of credits deposited in pooled buffer account. [70]		For GHG projects with a risk of reversal of GHG emission reductions or removals, Project Proponents shall analyse and mitigate risk, and monitor, report, and compensate for reversals. [78]		Post-closure requirements to address the risk of reversal is methodology specific. CO_2 removal supplier must provide a risk assessment and mitigation plan for the risks related potential re-emission of CO_2. [81]

Table 8: Mapping of carbon leakage provisions for carbon removal in five carbon crediting programmes.

	Verra	Gold Standard	ACR	CDM	Puro

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[70] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf section 2.4; 2.4.1

[78] https://acrcarbon.org/wp-content/uploads/2023/10/ACR-Standard-v8.0.pdf

[81] https://unfccc.int/sites/default/files/resource/sb006_pubic_conslutations_removals_Puro.earth_.pdf

Carbon leakage provisions	**Assessment of leakage potential and leakage management** (leakage mitigation activities listed in the VCS Standard**).** **Quantification and deduction from CO_2 removals according to applied methodologies.** **Monitoring of leakage.** The potential for leakage shall be identified for AFOLU projects, and projects are encouraged to include leakage	**Assessment and deduction of leakage emissions from tCO_2 from total biomass to determine the net tCO_2e sequestered by the project**. Baseline, leakage, and project emissions, both in tCO2e, are deducted from the tCO2e from total biomass. This gives the net tCO2e sequestered by the project.[85] Formulas are provided for A/R projects.[86]	**Assessment and deduction of leakage emissions.** ACR requires Project Proponents to address, account for and mitigate certain types of leakage, according to the relevant sector requirements and methodology conditions. Project Proponents must deduct for leakage that reduces the GHG emission reduction and/or removal benefit of a GHG project in	**Assessment and deduction of leakage emissions.** Project design documents must include measures to be implemented to minimise potential leakage; a description of formulae used to estimate leakage.[88] CDM provides different tools on accounting for leakage from particular project types.[89]	**Assessment of leakage potential. Quantification and deduction from CO_2 removal.** CO_2 Removal Supplier assesses all potential sources of leakage (i.e., increase of fossil emissions) outside of the project activity boundary but due to it as specified in the Methodology. In the case where leakage potential is identified it shall be quantified and deducted from the CO_2 removals. [90]

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[85] https://goldstandardhelp.freshdesk.com/support/solutions/articles/44001989676-how-is-the-carbon-stored-in-forests-measured-
[86] https://www.goldstandard.org/sites/default/files/ar-requirements_v0-9.pdf
[88] https://cdm.unfccc.int/Reference/COPMOP/08a01.pdf#page=6 C 22.; Appendix A (g), Appendix B, 2. (f); 2. (p) (ii)
[89] https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf
[90] https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/General%20Rules/Puro%20Rules%20v3.0.pdf

	management zones as part of the overall project design.[82] Verra has provided a module for estimating leakage from ARR activities.[83] Mitigation activities listed in section 3.15.7 of VCS Standard version 4.5. Quantification details in sections 3.15.8 – 3.15.15 of VCS Standard version 4.5. Project market leakage assessments will be subject to periodic review by Verra. This process consists of a review of a sample of AFOLU projects'	excess of any applicable threshold specified in the methodology.[87]

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[82] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf 3.15.6
[83] https://verra.org/wp-content/uploads/2021/12/ARR-Leakage-Tool.pdf
[87] https://acrcarbon.org/wp-content/uploads/2023/10/ACR-Standard-v8.0.pdf

	leakage assessments to identify any inconsistencies in the process and application of the leakage requirements. [84]

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[84] https://verra.org/wp-content/uploads/2023/08/VCS-Standard-v4.5.pdf

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This report has been reviewed and approved in accordance with IVL's audit and approval management system.