# Carbon negative handbook

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CARBON MARKET WATCH

BELLONA EUROPA

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# ABBREVIATIONS

| | |
|---|---|
| **BECCS** | Biomass energy with Carbon Capture and Storage |
| **BioCCS** | Biomass with Carbon Capture and Storage |
| **C** | Carbon |
| **CAP** | Common Agricultural Policy |
| **CCS** | Carbon Capture and Storage |
| **CCU** | Carbon Capture and Utilisation |
| **CDR** | Carbon Dioxide Removal |
| **$CO_2$** | Carbon Dioxide |
| **$CO_2e$** | Carbon Dioxide Equivalent |
| **CRCF** | Carbon Removal Certification Framework |
| **DACCS** | Direct Air Capture with Carbon Capture and Storage |
| **EAFRD** | European Agricultural Fund for Rural Development |
| **ECL** | European Climate Law |
| **EU** | European Union |
| **ETS** | Emission Trading System |
| **EW** | Enhanced Weathering |
| **GAEC** | Good Agricultural and Environmental Conditions |
| **GHG** | Greenhouse Gas |
| **Gt** | Gigatonne ($10^9$ tonnes) |
| **Gt C** | Gigatonnes ($10^9$ tonnes) of Carbon |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LCA** | Life Cycle Assessment |
| **LULUCF** | Land Use, Land Use Change and Forestry |
| **MRVL** | Monitoring, Reporting, Verification, Liability |
| **MWh** | Megawatt hour |
| **Mt** | Megatonne ($10^6$ tonnes) |
| **NDC** | Nationally Determined Contribution |
| **NEGEM** | NEGEM H2020 research project |
| **NETP** | Negative Emission Technology or Practice |
| **NGO** | Non-Governmental Organisation |
| **NRL** | Nature Restoration Law |
| **NZIA** | Net-Zero Industry Act |
| **PB** | Planetary Boundaries |
| **REDD+** | Reducing Emissions from Deforestation and forest Degradation in developing countries and additional forest-related activities that protect the climate |
| **SLO** | Social License to Operate |
| **UNFCCC** | United Nations Framework Convention on Climate Change |

# Executive Summary

The 2015 Paris Agreement established the global ambition to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases (GHG) in the second half of this century". This is more commonly referred to as "net zero GHG emissions". To reach net zero targets, substantial gross emissions reductions of over 90% across all sectors (transport, energy, waste, industry, AFOLU) will be needed.

Realistically, only a small and limited amount of carbon dioxide removal (CDR) - defined as the removal and permanent storage of atmospheric carbon dioxide ($CO_2$) in stable reservoirs - can be achieved. Nonetheless, CDR will have a crucial role in counterbalancing residual emissions. Options include emerging negative emissions technologies and practices (NETPs) that enhance natural processes or use novel approaches. Each method spans a range of technological readiness, has potential physical limitations, resource dependencies, adverse impacts, and co-benefits. Given these trade-offs, as well as the challenges for storage permanence, liability for any reversals, and limits to upscaling removals, a diverse portfolio is required; no one technology or practice alone can address the challenge of removing the required amount of $CO_2$ by 2050. Moreover, the risks that come with relying on one single approach, or a small subset of approaches, must be minimised.

The handbook discusses a list of concepts relevant to CDR and explores six different NETPs: biochar, biomass with carbon capture and storage (BioCCS), direct air capture with carbon capture and storage (DACCS), terrestrial enhanced weathering, afforestation and reforestation, and soil carbon sequestration. It is aimed at policymakers, NGOs, journalists, and members of the public with an interest in CDR policy making. As such, it seeks to provide a robust summary of the core principles, concepts, technologies and practices underpinning CDR.

# Overarching policy recommendations

**1**

Adopt a robust definition for carbon dioxide removal, defined as the direct extraction of $CO_2$ from the atmosphere that is permanently stored; permanence is understood as lasting at least several centuries. The $CO_2$ taken out of the air must outweigh the corresponding amount of greenhouse gas (GHG) emissions sent into the atmosphere linked to the removal activity, thereby ensuring additional physical removal from the atmosphere has taken place.

**2**

Respect the hierarchy: use permanent removals and land-based sequestration as supplements to emission reductions, as opposed to substitutes for decarbonisation. Contribution claim models could be favoured as equating removals to emissions leads to false, unrealistic, and unsubstantiated claims.

**3**

Set realistic, separate, and legally binding targets and policies for emission reductions, permanent removals, and land-based sequestration. The differences between each activity should be recognised and addressed to avoid conflation and maximise their contribution to tackling the climate crisis.

**4**

Disaggregate net zero goals by GHG emission type (due to their different climate impact and atmospheric residence time) and removal/sequestration permanence and risk of storage reversal. Match the type and timescale of emissions with corresponding removal characteristics to accurately counterbalance these and to devise effective pathways towards achieving net zero.

# Overarching policy recommendations

## 5

Implement robust accounting rules, certification methodologies, liability mechanisms and sustainability requirements for CDR based on careful consideration of implications and impacts to ensure real and sustainable removals.

- Monitoring, reporting and verification (MRV) must be based on a comprehensive quantification formula, always using the most conservative estimates and taking into account all GHG emissions (direct and indirect) across the entire value chain, both domestically and abroad, where applicable.

- Prevent double-counting and double-claiming by applying consistent and unique identifiers to units sold on the private market or to third countries. Keep track of the removal certificates: make sure that the certification happens as and when the net removals occur, rather than before.

- Assign liability rules to ensure that relevant actors are held accountable for potential reversals, as well as to clarify transfers of liabilities, thereby avoiding the passing of an unfair burden to future generations.

## 6

Invest in research and development of CDR approaches and design policy mechanisms to allow for learning and encourage data transparency obligations that enable cross-jurisdictional knowledge sharing. View failures as learning opportunities and as a means to hold constructive discussions on the optimal deployment of CDR portfolios. To break down barriers to sustainable deployment, devise alternate pathways focussed on emission reductions with limited to minimal reliance on CDR.

# Overarching policy recommendations

## 7

Adopt a holistic perspective on Earth system stability, with policies that integrate climate stabilisation and biosphere stewardship that account for their equally fundamental role in supporting Earth system resilience. Integrate food system transformations, supporting a societal shift towards a plant-based diet that will free up land for nature restoration and sustainable production of biomass.

## 8

Deploy a combination of CDR approaches:

- Adopt a diversified portfolio of NETPs in order to satisfy a realistic and meaningful deployment of NETPs. Identify opportunities to deploy CDR approaches via their co-benefits, rather than for the purpose of carbon removal.

- Adopt country-specific portfolios within realistic and responsible negative emission pathways for the EU. These consider the individual country's characteristics and apply a sustainable supply-driven approach, as opposed to one that is demand-based. Take pressure off constrained resources by ensuring effective allocation between mitigation activities.

## 9

Foster international cooperation in climate mitigation policy to encourage best use of regional bio-geophysical resources and respect for socio-economic factors, whilst compensating for the uneven distribution of CDR potentials across the world and taking historical responsibility into account.

# Overarching policy recommendations

## 10

Treat CDR as a public good and integrate environmental and social concerns throughout policymaking, with particular regard to public consultation, transparency, robust governance, human rights, and just transitions. Include communities in CDR projects from inception, clearly define the relevant stakeholders, decision-making processes, and establish grievance mechanisms. Respect fundamental principles of international and European Environmental Law, such as the precautionary, do no (significant) harm, and the polluter pays principles. Adhere to the 1.5°C limit, as established in the Paris Agreement.

# Introduction

## CDR in a nutshell

“Carbon dioxide removal” (CDR) consists of physically extracting carbon dioxide ($CO_2$) already present in the atmosphere and permanently storing it, for example in geological formations. There are a variety of approaches to CDR; those leading to long-term storage and low vulnerability are commonly known as engineered or technical removals. Meanwhile, carbon dioxide can also be stored via natural processes in ecosystems such as forests, wetlands, and grasslands that act as natural carbon sinks. Considering these are at high risk of human and natural disturbances and require ongoing management, they are vulnerable to loss of stored carbon, and are therefore best viewed as temporary forms of storage. However, the traditional divide between biogenic and technical removals is illusory, as technical solutions such as biomass use with carbon capture and storage (BioCCS) and terrestrial enhanced weathering (TEW) also have a natural component to them. It should be noted that, where negative emissions occur through the biological carbon cycle, this can create additional benefits such as biodiversity protection and soil health.

Despite a myriad of uncertainties existing over the different removals concepts, the IPCC has asserted that CDR is unavoidable if the 1.5°C temperature goal is to be respected - with no or limited overshoot - and global net zero greenhouse gas (GHG) emissions is to be reached. According to the IPCC, the role of CDR is to:

1. Before net zero, supplement emission reductions and accelerate climate change mitigation.
2. Achieve net-zero by balancing out residual $CO_2$ and non-$CO_2$ GHG emissions.
3. Exceed annual GHG emissions and achieve “net negative” emissions globally to draw down global temperatures.

The mitigation hierarchy demands that emission reductions remain the priority - a situation where overreliance on CDR undermines decarbonisation efforts must be avoided at all costs. Moreover, emissions must be reduced by at least 90% to reach a balance with the likely limited quantity of $CO_2$ that will be removed from the atmosphere, a state known as “net zero” (see Figure 1 for indication of potential supply and demand for CDR). In the EU, the Climate Law states that the bloc must achieve net zero by 2050 at the latest, recognising that net zero is a temporary, intermediary target; the ultimate goal must be to reach “net negative”, a state where more $CO_2$ is removed from the atmosphere than equivalent GHGs are emitted.

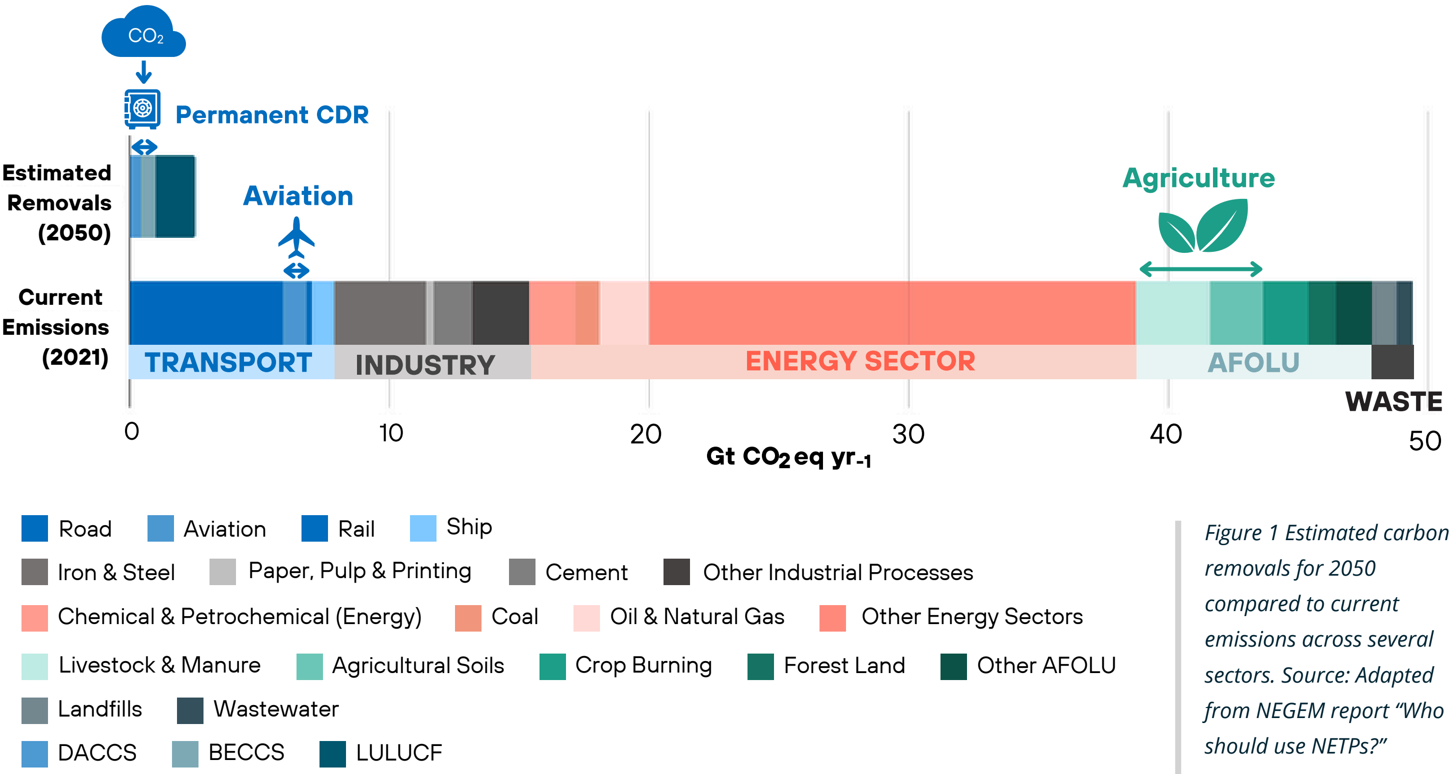


*Figure 1 Estimated carbon removals for 2050 compared to current emissions across several sectors. Source: Adapted from NEGEM report “Who should use NETPs?”*

Another important consideration is how to tackle residual, hard to completely abate emissions. Given the likely limited capacity for CDR, its role should be limited to counterbalancing the final remaining emissions. The issue is defining under what conditions - if any - emissions can be allowed to be classified as residual. Which activities do we, as a society, deem too precious to forgo, despite the climate damage they cause? No sector is impossible to decarbonise, but agreement over what classifies as residual is variable, depending on technological availability, societal necessity or the economic conditions at any point in time. Hence, to avoid mitigation deterrence, a strict definition of residual emissions is required.

There are many uncertainties surrounding CDR, primarily due to the physical limitations in the natural environment, the need for sustainable resource use, as well as technological, economic and societal constraints. As such, there is an imbalance between the "demand" and "supply" potential for CDR, significantly lowering the likelihood of large-scale CDR deployment. Certainly, a diverse portfolio of CDR approaches must be implemented, but national capacity and resources are also likely to vary, resulting in an unequal distribution in the ability to cost-effectively remove carbon from the atmosphere. This needs to be reconciled with the idea that some countries have greater historical greenhouse gas emissions and financial capacities, thus bearing greater responsibility if climate action is to develop fairly. Ultimately, however, to achieve net zero at a global system level, CDR must be viewed as a public good - everyone benefits from the decreasing atmospheric GHGs, just as everyone is harmed by their increase.

## Core CDR principles

A robust definition of what qualifies as CDR is critical to ensuring that there is a net reduction in atmospheric $CO_2$ concentrations and that more carbon is removed than the equivalent amount of GHG emitted by the removal activity. Below are four principles, set out by *Tanzer and Ramirez*, explaining what should qualify as CDR:

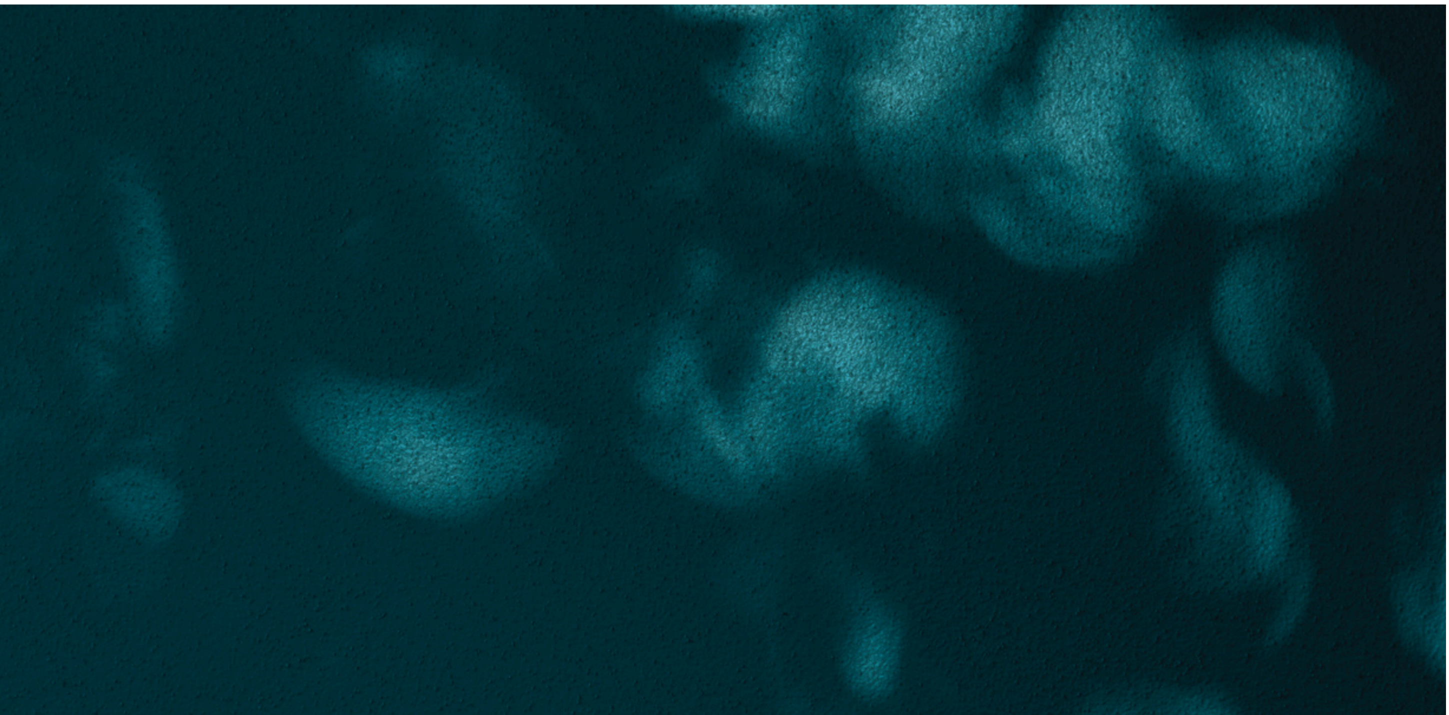
1. $CO_2$ is physically extracted from the atmosphere.
2. The extracted atmospheric $CO_2$ is permanently stored out of the atmosphere.
3. All greenhouse gas emissions associated with the removal and storage processes are comprehensively estimated and included.
4. More atmospheric $CO_2$ is permanently stored than GHGs are emitted in the removal and storage processes and their complete supply chains.

Extracted carbon can be stored in a variety of reservoirs that can generally be separated into “biological”—such as in vegetation or soils and sediments—“geochemical”, and “geological” carbon stores as well as ocean reservoirs. There are fundamental differences between these storage mediums regarding reservoir stability, how easy it is to quantify and monitor the stored $CO_2$, the required management and maintenance effort, and the assignment of liabilities in the event of a reversal of carbon storage.

## Objectives of the CDR handbook

The objective of this handbook is to render CDR accessible to policymakers, NGOs, journalists, and other interested actors. It aspires to increase common knowledge on CDR and help those at the heart of policymaking to internalise current understanding on what does or does not qualify as a real removal, the limitations to feasibility and large-scale deployment, as well as the core policy recommendations to sustainably deploy CDR in the journey towards net zero and beyond.

The handbook is split into two parts: the first discusses a variety of CDR concepts, while the second provides a visually engaging review of the different NETPs, addressing key facts, advantages and disadvantages, constraints, future research, and recommendations.



# Key concepts for carbon dioxide removal

## Accounting and additionality

Accurate and robust carbon accounting is essential to quantify net removals, and to assess the environmental trade-offs. In principle, accounting can appear straightforward, but there are numerous challenges due to the complexity of CDR systems, their spectrum of associated emissions, and their many possible trade-offs or co-benefits.

These issues can be resolved by developing science-based frameworks that enable explicit accounting for different capture and storage types, and improve data quality.

Separating accounting frameworks minimise the risk of mitigation deterrence (where removals are used to slow down decarbonisation efforts) and of drawing a false equivalency between emissions reductions and removals.

Setting an appropriate and comprehemsive system boundary is important as this will define which emissions are accounted for (such as emissions occurring downstream), those that are not, and who is responsible for those emissions.

Accounting and certification should happen as the carbon storage occurs to ensure any carbon debt is also accounted for at the time of storage. This is particularly important for biomass-based solutions (e.g. BioCCS) or for non-permanent sinks that require sustained carbon stock management (e.g. forest management).

## What is carbon accounting?

Carbon accounting aims to quantify and track carbon flows for a defined system. It aligns the physical science with climate responsibility by clarifying the metrics, methodologies, jurisdiction, and liability to track progress on climate targets and net zero ambitions.

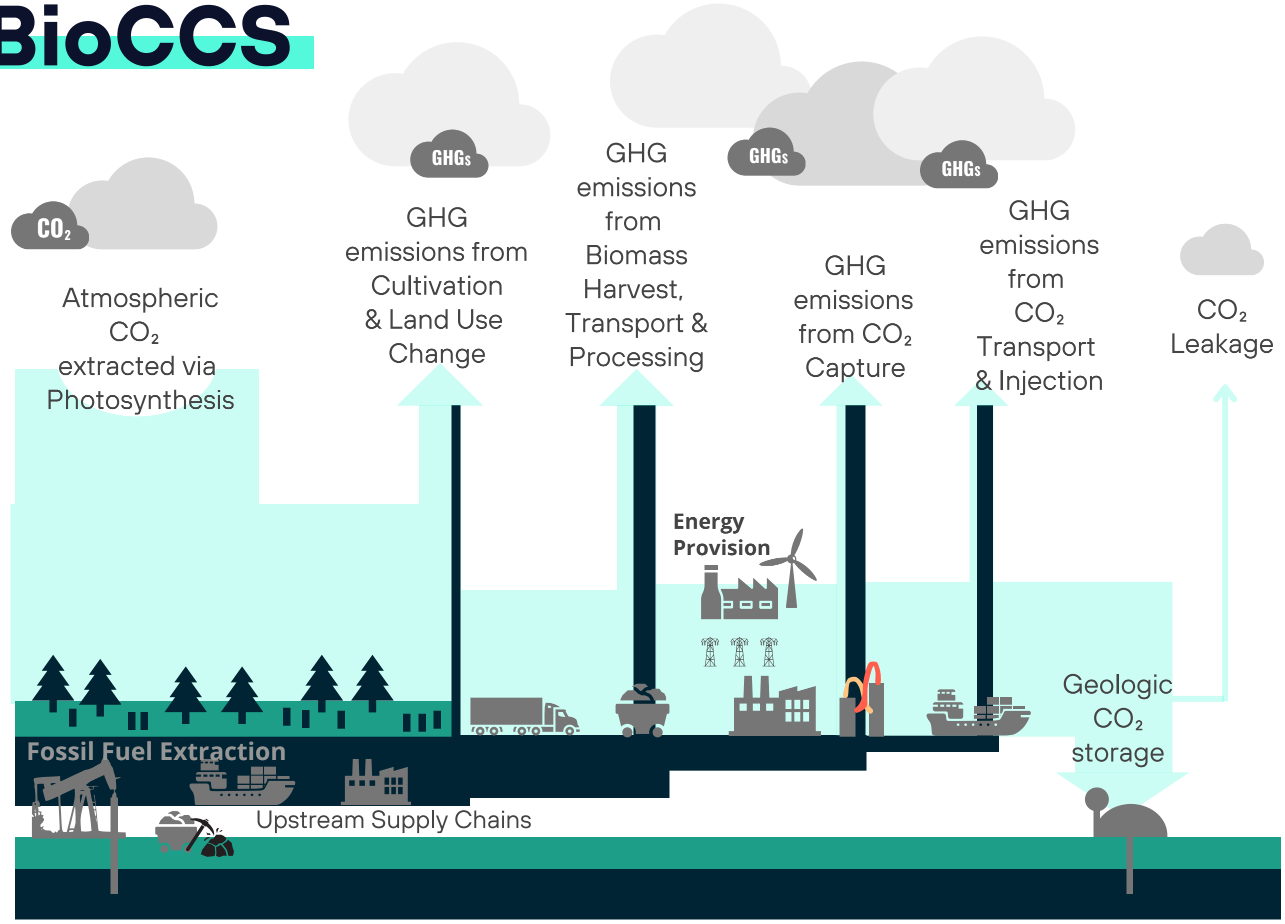
Accounting of GHG emissions is common practice for countries within the UNFCCC, but also increasingly for businesses and other entities to meet regulatory reporting obligations under the Corporate Sustainability Reporting Directive (EU Directive 2022/2464). GHG emissions are accounted for using a territorial, or "production-based", approach to accounting. Territorial accounting creates an inventory of GHG emissions (see "Source" and "Sink") within a country's border or national jurisdiction. Emissions can be monitored directly where they are produced, such as at the stack or vent of a point source or calculated from mass balances (e.g. carbon stock change from land use change), estimated using empirical-based models, or by applying appropriate emissions factors.

## Why is carbon accounting relevant for CDR?

The climate benefit of carbon dioxide removal arises from extracting $CO_2$ from the atmosphere and storing it permanently, thus reducing the amount of $CO_2$ that is in the atmosphere. This means that each CDR approach must physically remove and store more $CO_2$ than the GHGs emitted in the removal and storage process (see also the Introduction for the four key principles that define what CDR is).

CDR certification should only count real removals that deliver net negative emissions. The certification of any CDR must be supported by comprehensive and robust carbon accounting to ensure that this net amount of atmospheric $CO_2$ removed is correctly quantified from "cradle-to-grave". As a result, the carbon budget of the system is complete from source to sink. This means carbon flows are tracked and recorded from any upstream emissions prior to atmospheric extraction and capture (cradle) through to storage (grave), including both direct and indirect emissions that may result from fossil fuel use or land use change. Leakage of carbon along the value chain and from a reversal of storage must also be considered (Figure 2). This type of carbon accounting at a project level is called life cycle system accounting.

# BioCCS



# Biochar

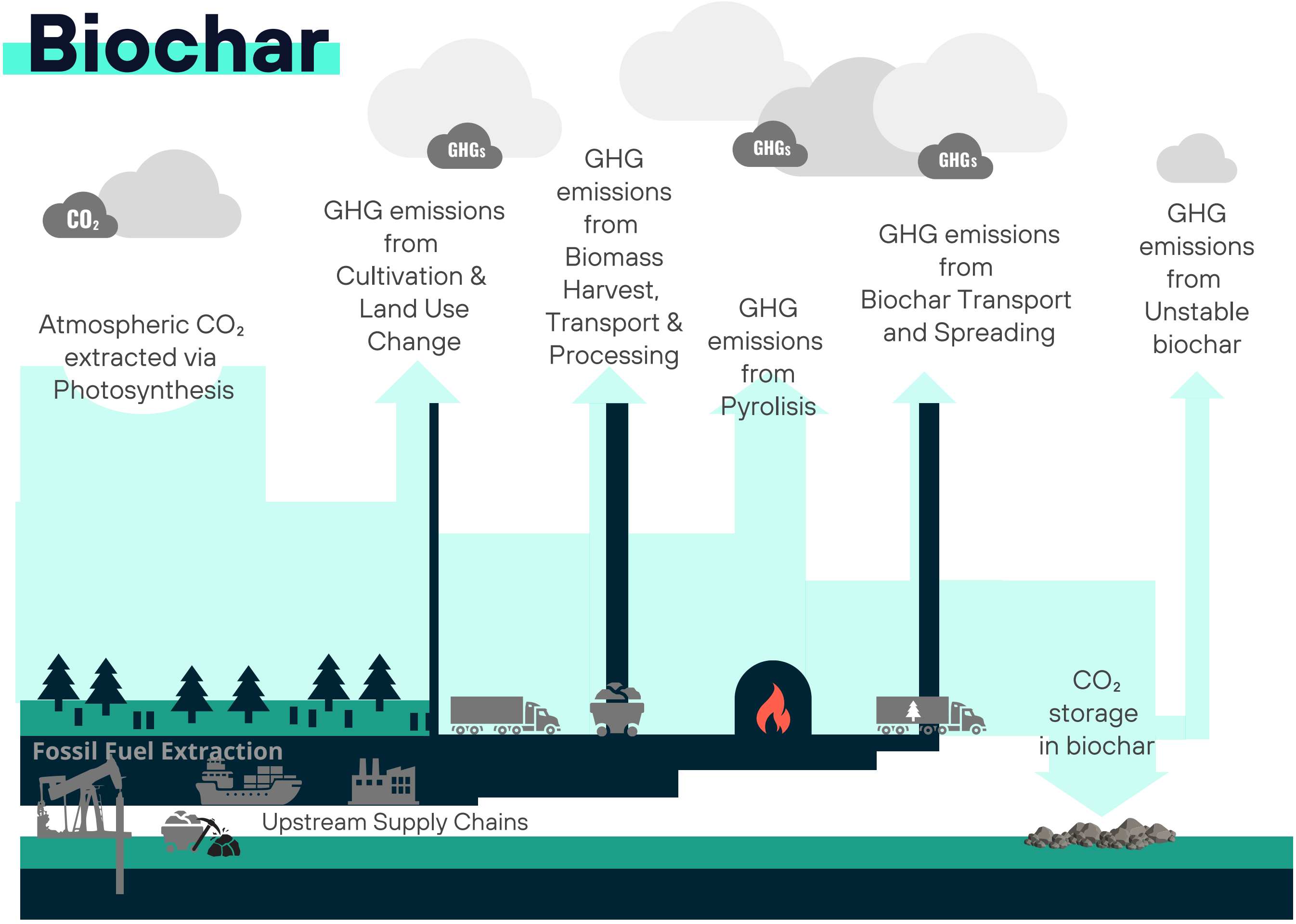


*Figure 2 Two examples of CDR systems for BioCCS (top) and biochar (bottom), which define the source, sink and system. Fossil fuel emissions sources and leakage of captured $CO_2$ along the entire value chain are also identified. Figure modified from Tanzer et al. 2022.*

Risks include:

- **Overcounting how much carbon is extracted and stored.** This risk can be minimised by standardising accounting protocols for different approaches. This means high quality empirical data, ideally sourced from direct measurements that quantifies capture and storage rates, is collected from each project and each location. Removals should also only be counted after they physically occur.

- **Undercounting associated emissions.** This risk can be minimised by setting a comprehensive definition of the CDR system components accounted for across the full value chain. For biogenic $CO_2$, the scope of each system cannot be generalised, but given the need for a "cradle-to-grave" approach, carbon accounting methodologies should strive for a wider and systemic view on associated emissions than the capture and storage facility itself.

- **Discounting the risk of storage reversal.** This risk can be mitigated by separating the sinks based on the reversal risk. This means that biogenic sinks with a high reversal risk, are accounted separately from geological sinks that are more secure and have storage lifetimes of >100,000 years. Developing separate policy instruments for each type of removal is also likely to be necessary (see also "Separation of activities and the need for separate targets").

Once the amount of net removed carbon is quantified, it can then be assigned a value or a unit that can be used in certification schemes and, for example, to counterbalance residual emissions. Systemic carbon accounting is also needed to determine who has the right to claim a removal. Depending on the accounting approach taken, this could be a country (territorial approach) or a commercial or public entity.

In life cycle accounting, the emissions and removals are assigned to the system itself, thus allowing the total net removal of the project to be methodically estimated. However, a technology system is not a liable actor. In territorial accounting, emissions and extractions are assigned to liable actors (nation states). However, from the annual sectoral accounting, it is not possible to determine if a specific CDR system has resulted in net removal, and not all emissions from that CDR system may be assigned to a liable actor.

Both life cycle accounting and territorial accounting respond to time in ways that can distort perceptions of when emissions and removals occur. In territorial accounting, the emissions and extractions are accounted for in the year that they occur, with $CO_2$ embodied in biomass accounted for as a removal during its growth, an emission when it is harvested, and again as a removal when it is captured for the purposes of geologic storage. Furthermore, as emissions from land use are accounted for by the total change in carbon stocks in a given year, it is not possible to precisely measure the specific growing time and carbon uptake speed of the biomass used in a BioCCS system.

The UNFCCC framework is focused on annual emission balances. Therefore, if extractions/emissions from long-rotation biomass, or biomass that is harvested, used, and/or stored, or associated supply chains occur in different years, there will not be a single inventory available that accounts for the total net emissions associated with the BioCCS system. Life cycle accounting, in contrast, typically compresses into the single “net $CO_2$ equivalent” metric, also obscuring any temporal delay. Emission factors for biomass that incorporate the global warming potential of the temporary residence of biogenic $CO_2$ in the atmosphere (until regrown by new biomass) have been proposed, but are not in widespread use, and still leaves the timing unclear.

## Challenges for accurate and coherent carbon accounting

- Different accounting rules apply in different countries (Annex 1 signatories vs. non-Annex 1 signatories) or sectors, which can generate loopholes. With biogenic $CO_2$ accounting, for instance, biomass used in bioenergy applications is “zero-rated”. This is because the $CO_2$ is accounted for as emitted during harvesting in the LULUCF sector, which means that, on paper, any captured biogenic $CO_2$ creates negative emissions.

- Transboundary accounting between countries will be needed as the steps in a CDR system are often different across different countries. Captured $CO_2$ (liquified, biomass, other materials) may need to be transported by ship or pipeline to final storage sites, or for further processing.

- Some CDR approaches have highly dispersed storage of $CO_2$ or capture processes that are slow and cumbersome to track. This means that there is higher uncertainty in the amount of carbon captured and stored.

- Use of partially recycled materials and mixed waste with carbon of both biogenic and fossil origin makes it difficult to accurately determine the source of carbon emissions and if a $CO_2$ net removal has genuinely taken place.

Carbon removals must demonstrate that the carbon removal would not have otherwise happened without this project. This additionality principle means that the activities are on top of what is required under standard practices, regulatory requirements, market activities, or what would have occurred anyway in the natural environment. These correspond to different categories of additionality, defined below:

**Physical additionality:** The activity results in a physical removal of additional carbon above baseline conditions. The carbon stored in a natural carbon sink without human intervention cannot be claimed for carbon credits. Moreover, in a carbon removal, project additionality, should also be demonstrated beyond the project area to ensure carbon loss is not shifted from one area to another. This type of additionality is fundamental and can be used to improve GHG inventories.

**Financial additionality:** The activity results in additional spending to achieve the carbon stored, rather than relying on passive and ongoing financial activities. Carbon-related financial flows were needed to make this activity economically viable. This type of additionality is secondary and is used to pair specific financial flows to a specific climate outcome.

**Regulatory additionality:** The activity results in additional carbon stored beyond standard practice and current regulatory requirements. This type of additionality is secondary and is used to ensure carbon-related finance going towards the activity enables it to take place.

Proof of additionality in all aspects is needed to avoid over-crediting of removals or emissions reductions and must be demonstrated above a baseline. Additionality is the measure of the extra climate benefit a certified activity brings, rather than impacts that would have occurred anyway e.g. a forest or soil that had to be restored under nature protection laws and current subsidy schemes. Accurate baselines are key to calculate physical additionality. Baselines should, ideally, take into account local environmental conditions and variability at the project level with standardised measuring, reporting and verification requirements.

# Carbon capture and storage (CCS) and use (CCU)

Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS) are frequently conflated and misrepresented as forms of CDR. CCS and CCU are technological pathways that reduce or delay emission of $CO_2$ to the atmosphere. They have different climate mitigation roles to CDR, which removes existing $CO_2$ from the atmosphere and stores it permanently. Each of these activities must therefore be clearly distinguished from one another.

By permanently storing $CO_2$, CCS (and some CCU pathways) can prevent $CO_2$ generated in an industrial installation from reaching the atmosphere and can abate emissions from sectors with few or no alternatives for decarbonisation. For CCU, the climate benefit comes from emission reductions if CCU products replace counterfactual products with higher life-cycle emissions.

CCS and CCU are energy intensive processes that risk increasing the cost while lowering the overall efficiency of that system. A system involving carbon capture demands additional energy and material input to produce the same final product output, compared to a system without carbon capture.

$CO_2$ captured is either used *in situ* (within the industrial cluster) or transported for storage or subsequent industrial use, requiring reliable and costly $CO_2$ transport infrastructure. This can also lead to higher associated emissions and infrastructural costs.

As with CDR, all emissions in the CCS and CCU value chain need to be calculated and accounted for, including the $CO_2$ source and fate.

## What is CCS and CCU?

Carbon Capture and Storage (CCS) is the capture of $CO_2$ and subsequent compression and storage in geological formations, or through mineralisation, resulting in permanent storage away from the atmosphere for potentially millions of years. Carbon Capture and Utilisation (CCU) is the process by which $CO_2$ is captured and directly or indirectly used in products or industrial processes. $CO_2$ storage has been regulated in the EU since the 2009 in the Directive on the geological storage of carbon dioxide (the so-called CCS Directive) and can be used to avoid the surrendering of ETS emission allowances if applied to an EU ETS-compliant installation. Industrial installations applying CCU must always surrender allowances for the $CO_2$ generated, unless the $CO_2$ is used in a manner whereby it is permanently chemically bound in a product during both its use and end-of-life.

CCU is also partially regulated in the Directive on the promotion of the use of energy from renewable sources, which promotes renewable fuels of non-biological origin, and fuels produced from captured $CO_2$. Nevertheless, a comprehensive regulatory framework across the entire value chain is currently lacking, with the European Commission planning some legislative initiatives to address this. Importantly, the Net Zero Industry Act (NZIA) sets a target for $CO_2$ storage injection capacity of 50 Mt per annum by 2030, placing an obligation on EU oil and gas producers to develop these storage sites. Furthermore, the NZIA lists CCS, CCU and $CO_2$ transportation as so-called “net zero technologies” and calls on the Commission to produce legislation on a potential market for captured $CO_2$. Lastly, the Communication on Industrial Carbon Management highlights the role carbon capture must play for the EU to reach its net zero targets, as well as the need for non-discriminatory, open-access, transparent, multimodal and cross-border $CO_2$ transport and storage infrastructure.

## Why are CCU and CCS relevant for CDR?

CCU and CCS are frequently conflated and misrepresented as forms of CDR. These need to be clearly differentiated to appropriately reflect the climate impact and develop utmost clarity on the climate benefit for these distinct actions.

CCS and CCU are processes or pathways, whereas CDR is an outcome of specific source-to-sink pathways. CCS and CCU can be a component of a CDR system only if the source of the $CO_2$ is atmospheric (DACCS and DACCU) or biogenic (BioCCS or BioCCU). It is only a removal if the captured carbon is stored permanently.
With CDR based on CCS, carbon is stored in geological reservoirs for at least several centuries, whereas CDR based on CCU can lead to storage in products where permanence lasts anywhere from a few days to a few decades, depending on the specific uses and the possibility to recycle the product in question. As such, carbon storage times through CCU tend to be shorter than the atmospheric lifetime of carbon and thus likely not permanent.

CCS and CCU from industrial or fossil sources do not extract past emissions from the air but prevent new ones from happening. Current technologies can technically capture upwards of 90-95% of $CO_2$ generated from the exhaust of a point source emitter. The primary barrier to doing so on a commercial level is economic - any additional percentage captured leads to a non- linear increase in the cost of doing so. Indeed these pathways are energy-intensive, with CCS typically consuming 1-3 MWh/tonne of $CO_2$, thereby increasing systems costs and lowering overall efficiency, since more energy is needed to produce the same output. The majority of the energy penalty stems from the capture of the carbon, or more accurately, the processes that separate the carbon from the gas composition. Thus, capturing carbon from the atmosphere requires more energy than from industrial flue gases, where concentrations are higher.

The captured carbon can be transported for storage (CCS), or subsequent industrial use or used in situ within the industrial cluster (CCU). This requires robust and costly $CO_2$ transport infrastructure, involving pipelines, ships, road and/or rail transport, which can entail significant emissions and efficiency losses, given the potentially vast distances between emitters and storage sites.

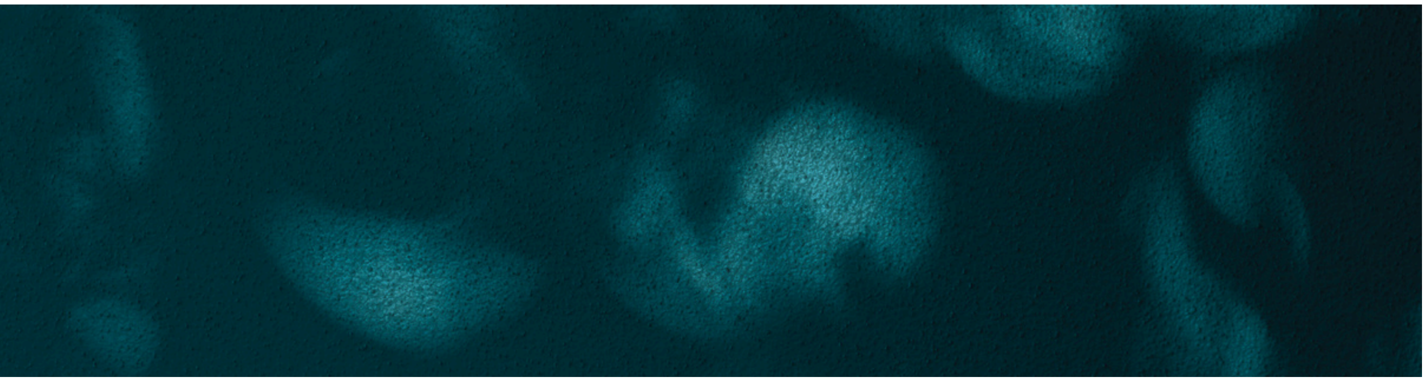
In this sense, all emissions in the CCS and CCU value chain need to be calculated and accounted for, which is no easy feat. Moreover, storage sites must be closely monitored, and a liability mechanism must be established should leakage arise. The EU has such a liability mechanism in the CCS Directive.

CCS and some CCU, from fossil or industrial sources, such as carbonated products which chemically bind the carbon permanently under normal use and end of life, can result in emissions reduction. In fact, the greatest climate benefits for CCS stem from tackling process emissions from industrial applications. If incentives are poorly designed, captured $CO_2$ can instead be used to extract more fossil fuels, a practice known as enhanced oil or gas recovery, which is common in the USA.

Clarity on terminologies and robust accounting can help remove any ambiguity on the climate impact of CCS and CCU depending on source of carbon and its end fate. CCS is not a silver bullet solution; CCS plays a role in cases where other emissions reductions options are technologically difficult or impossible. With targeted use, CCS has a pivotal role to play in Europe’s green and just transitions and ensures that these economically important and largely welfare-carrying sectors can be part of a net zero world. In the long term, $CO_2$ transport and storage infrastructure networks are also needed for some CDR approaches, without which we will not be able to reach our climate goals.

## The Carbon Cycle

Due to interconnection of carbon flows in the natural environment, any change in a carbon flow, such as putting carbon into or out of the atmosphere, will influence other components of the carbon cycle. Just as the ocean and land sink currently absorb excess atmospheric $CO_2$, the reverse could also happen if atmospheric $CO_2$ concentrations decline.



# What is the global carbon cycle?

The global carbon cycle refers to the complex network of carbon reservoirs – underground, on land, in the ocean and atmosphere – and flows of carbon between them. Over 37,000 Gt of carbon (Gt C) is stored in the oceans, with a further 1,700 Gt C stored in soils and 400 Gt C in vegetation. An additional 900 Gt C is found in fossil carbon reserves (natural gas, oil, and coal) in the Earth's crust as well as around 885 Gt C in the atmosphere (see Figure 3).

Geochemical, biological, and chemical processes transfer carbon between different reservoirs as sources and sinks of carbon to the atmosphere (Figure 3). Such processes include the slow uptake of atmospheric $CO_2$ via natural rock weathering and transport of the dissolved carbon via rivers and lakes to the ocean (geochemical), rapid biological uptake by photosynthesis in vegetation and marine primary producers, transfer of organic carbon to soils and seafloor sediments, as well as the chemical carbon exchange between the ocean and atmosphere ("air-sea gas exchange"). Geochemical carbon reservoirs such as rock minerals, and associated processes such as natural rock weathering are sometimes referred to as the "slow" carbon cycle as the carbon exchange takes place over periods spanning thousands to millions of years. Conversely, in biogenic reservoirs or biological processes such as photosynthesis, carbon is exchanged on a day-to-week basis and is therefore frequently referred to as the "fast" carbon cycle.

The carbon is contained in a variety of chemical forms:

- organic carbon in living and dead biomass in the ocean, on land, and in soils
- gases such as methane and carbon dioxide, in the atmosphere
- minerals such as carbonate-containing rocks, including underground

Geochemical, biological, and chemical processes transfer carbon between different reservoirs as sources and sinks of carbon to the atmosphere (Figure 3). Such processes include the slow uptake of atmospheric $CO_2$ via natural rock weathering and transport of the dissolved carbon via rivers and lakes to the ocean (geochemical), rapid biological uptake by photosynthesis in vegetation and marine primary producers, transfer of organic carbon to soils and seafloor sediments, as well as the chemical carbon exchange between the ocean and atmosphere ("air-sea gas exchange").

Geochemical carbon reservoirs such as rock minerals, and associated processes such as natural rock weathering are sometimes referred to as the “slow” carbon cycle as the carbon exchange takes place over periods spanning thousands to millions of years. Conversely, in biogenic reservoirs or biological processes such as photosynthesis, carbon is exchanged on a day-to-week basis and is therefore frequently referred to as the “fast” carbon cycle.

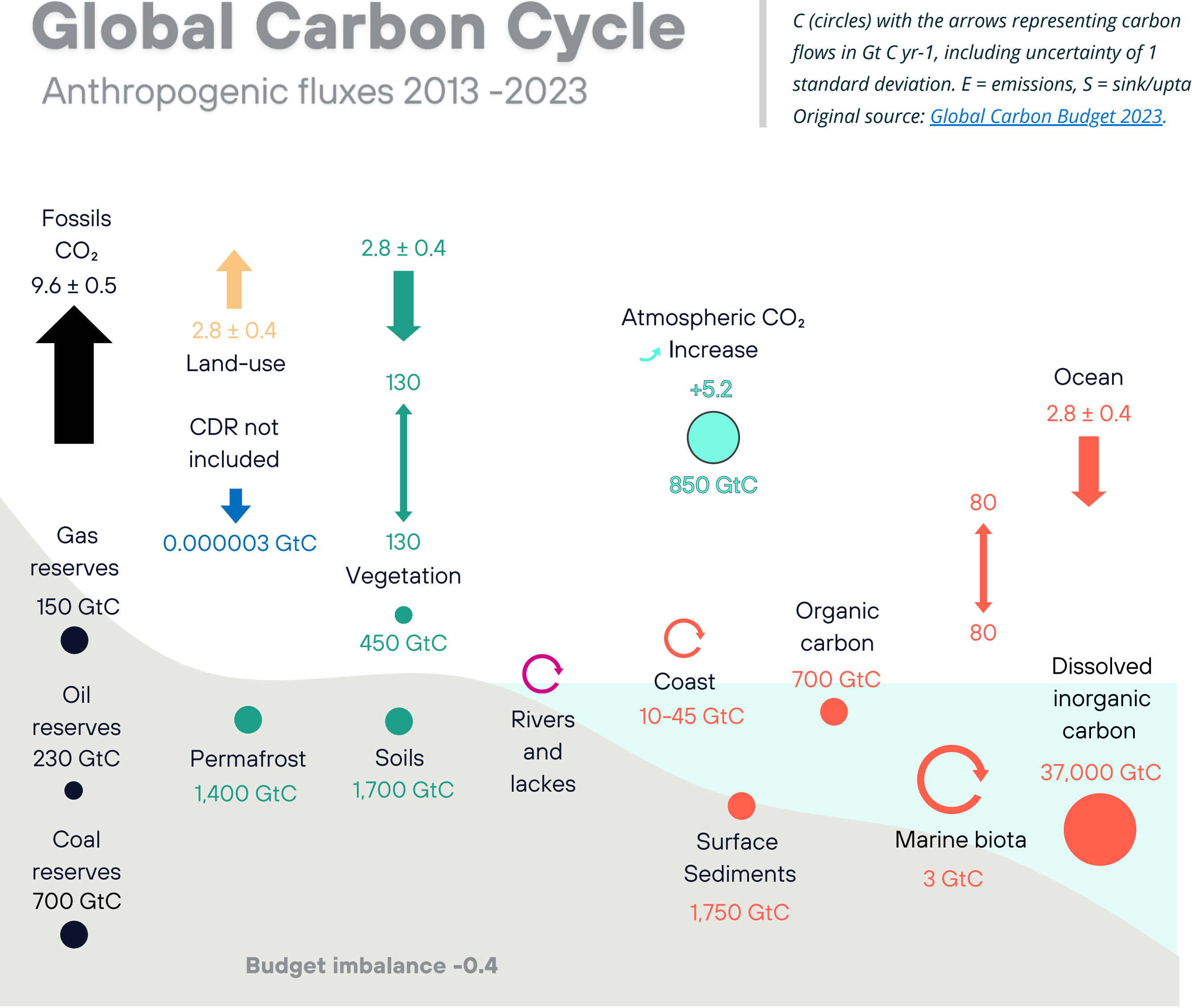


*Figure 3 Overview of the carbon cycle. Circles indicate the global average carbon reservoirs in Gt C (circles) with the arrows representing carbon flows in Gt C yr-1, including uncertainty of 1 standard deviation. E = emissions, S = sink/uptake. Original source: Global Carbon Budget 2023.*

The carbon is contained in a variety of chemical forms:

- organic carbon in living and dead biomass in the ocean, on land, and in soils
- gases such as methane and carbon dioxide, in the atmosphere
- minerals such as carbonate-containing rocks, including underground
- dissolved ions such as bicarbonate, in groundwater and the ocean

Although these processes work on a range of timescales, from days up to millennia, carbon sources and sinks are closely coupled, and the amount of carbon in each reservoir is relatively stable. However, the extraction of fossil carbon from deep in the Earth's crust and emission to the atmosphere perturbs these equilibria. Only ~40% of the $CO_2$ emitted from human activities remains in the atmosphere because ocean and land sinks absorb substantial amounts of this excess carbon (25% and 35% in 2022, respectively).

## Why is the carbon cycle relevant for CDR?

Avoiding an emission has a different climate impact to removing the same amount of carbon after emission. This is because the carbon cycle is full of complex carbon-climate feedbacks that work on different time scales. Hence, the cooling effect of removing carbon will not be immediate and may not be fully effective. Research indicates that the warming impact of $CO_2$ emissions is higher than the cooling impacts of removing $CO_2$. Hence, an overshoot scenario (i.e. where $CO_2$ concentrations temporarily exceed an agreed limit and excess atmospheric $CO_2$ is removed to remain within the carbon budget) has a different climate warming influence than a non-overshoot scenario, due to this difference in the transient climate response to cumulative carbon emissions and the potential for triggering tipping points in the global climate system that cannot be undone by CDR.

Climate impacts of carbon removal may differ between CDR type and over time due to the carbon cycle and climate feedback: for instance, more carbon needs to be removed under reforestation than in ocean alkalinity enhancement to achieve the same reduction in warming. This is due to biophysical feedbacks (albedo changes) from the increased vegetation from reforestation that ocean alkalinity enhancement does not have. Quantification and certification of removed carbon can occur once it has already been removed (*ex-post*), or by estimation of the amount of carbon that will be removed in future (*ex-ante*). For CDR approaches, where the removal does not happen immediately (e.g. enhanced weathering), ex-post certification ensures that future potential removals may not be used to counterbalance contemporaneous emissions.

## Carbon market mechanisms

Carbon markets apply a price and/or limit on emissions. There are two predominant types of carbon market mechanisms - emission trading systems and carbon crediting mechanisms, such as the voluntary carbon market. Currently, there is no robust equivalent market-based mechanism for removals because it cannot be proven that one carbon credit reliably neutralises or counterbalances the impact one tonne of $CO_2$ emitted has on the climate.

The responsibility to fund removals should not be left to voluntary markets, which tend not to acknowledge differences in storage reliability between natural and geological sinks, and are likely to favour the cheapest removal option, as opposed to a diverse portfolio.

Alternative solutions are needed. Possible options include: a dedicated Removal Trading System for high-quality, permanent removals; use of carbon market revenues; or a contribution model, whereby companies use existing carbon markets to disburse climate finance by buying and cancelling carbon credits, without claiming ownership of the emission reductions or making offsetting claims, could be adopted.

## What are carbon market mechanisms?

Carbon markets are market-based instruments used to limit carbon pollution. They aim to reduce emissions by putting a price and/or a limit on emissions (primarily carbon dioxide) or by creating other forms of financial incentives to reduce emissions. Currently, no robust market-based mechanism exists to comprehensively tackle removals at a global level, although policymaking discussions such as the UNFCCC negotiations on Article 6 of the Paris Agreement are ongoing.

The two most common carbon market systems are emission trading systems (ETS) and carbon crediting mechanisms. The former is a regulatory regime, with many examples across the world, and specifically in the EU, that seeks to reduce emissions from particular sectors. The latter is often established as a voluntary regime which incentivises the implementation of mitigation projects through a system allowing project developers to earn revenues from the sale of carbon credits. These markets are dominated by emission reduction projects, but also aim to increase carbon sequestration in the land sink. At the EU level, the newly agreed the Carbon Removal Certification Framework will certify, amongst others, carbon removal activities expected to operate in the voluntary carbon market.

An ETS - a type of cap-and-trade system - sets an overall limit (a “cap”) on the total volume of GHG emissions that companies in the covered sectors can cumulatively emit. The reduction targets are achieved through the gradual lowering of this cap. In the EU ETS, this cap takes the form of emission allowances or pollution permits which companies buy (or receive for free) and sell on the open market, and subsequently trade with one another. One allowance represents one tonne of $CO_2$. There is no limit to the amount of allowances that can be bought or the amount of times they can be traded. Once an allowance is surrendered, the right to emit one tonne of $CO_2$ materialises.

Given that the system is based on the “polluter pays principle”, the costs of pollution should be borne by those who create it. As such, companies purchase most of these allowances in order to pollute. Unfortunately, the EU ETS has historically been characterised by excessive supply and free allocation of pollution permits, leading to low prices on pollution and undermining the core objective of lowering emissions.

Conversely, in carbon credit mechanisms, project developers are awarded certified credits, issued by carbon-crediting programs or standards. One credit represents one tonne of $CO_2$-equivalent reduced (or removed from the atmosphere). These are then sold to private or public actors, who can subsequently trade the credits amongst themselves. There is no limit to the number of times a credit can be traded, and, in most cases, the credit does not expire. Once a final buyer decides to use a credit, to compensate for some of their emissions or to claim carbon neutrality, the credit is “retired”. As such, it can no longer be traded and no other claims to that credit or its underlying environmental or social attributes should be made.

## Why is carbon market mechanisms relevant to CDR?

Despite it being a mechanism designed exclusively for emission reductions, recent discussions on integrating CDR (or CDR credits) into a the EU ETS are gaining traction. Nonetheless, merging these could lead to a highly problematic scenario, where price prevails over quality, incentivising those removals that cost less than the price of pollution. Indeed, an ETS cannot be assumed to support the deployment of high quality permanent removals as these will be more expensive than the rest of the abatement available on the market. Market mechanisms for removals should also align with principles of physical and social credibility.

As for the crediting regime, a starting point of contention is the incorrect tonne-for-tonne equivalence; it cannot be scientifically proven that one carbon credit reliably neutralises or counterbalances one tonne of $CO_2$ emitted. In fact, a tonne of $CO_2$ removed may have up to 10% lower impact on the climate than a tonne emitted due to interactions with land and ocean carbon stocks. This false equivalence deters polluters from addressing their emissions as it allows them to buy credits and avoid reducing their carbon footprint.

Moreover, each tonne removed needs to be monitored and kept permanently out of the atmosphere, which is difficult to guarantee considering the natural life-span of a project from which credits have been emitted tends to be shorter than the atmospheric life-span of carbon. The project may no longer be under management, have released any carbon stored in vegetation or soils, or stopped reducing emissions. Indeed, for traded carbon credits to be of high quality, they must undergo MRV (see “Monitoring, Reporting, Verification, Liability (MRVL)”) and apply robust accounting procedures to avoid double counting. Investments generating credits must also: demonstrate additional results beyond what would have occurred naturally, should have a low risk of reversal, and avoid negative impacts on people and the environment.

Yet, crediting schemes often stem from nature-based projects, which frequently undermine the previously stated criteria. For instance, the REDD+ forestry projects (focused on reduction credits) have been highly criticised for generating exaggerated quantities of credits, having questionable climate impacts, and lacking adequate safeguards to prevent adverse impacts on the environment and local communities. Overall, such projects did not deliver climate benefits that are equivalent to the climate damage they were meant to offset, undermining environmental integrity.

The above reveals that markets may not be a suitable tool for funding removal and land-based sequestration activities, particularly where no separation between permanent removals, land-based sequestration and emission reductions is drawn within the relevant policy framework. As explained above, market rationalism primarily focuses on price rather than quality, meaning a poorly regulated market, without separation, would necessarily incentivise the cheapest option: land-based approaches that are inherently vulnerable to human and natural disturbances and thus prone to releasing sequestered carbon into the atmosphere.

In this vein, market rationalism also limits the possibility of adopting a wide CDR portfolio since expensive, sustainable and innovative CDR will never see the price signal it needs. Yet wide portfolios are necessary, both to reduce the risks associated with relying on one singular approach and to maximise the overall effectiveness of carbon removal and sequestration efforts.

Clearly, alternate solutions are needed. One option might be to create a dedicated Removal Trading System for high-quality, permanent removals only. Another option could use carbon market revenues to finance removals. Alternatively, a contribution claim model could be adopted, whereby companies use existing carbon markets to disburse climate finance by buying and retiring carbon credits, without claiming ownership of the emission reductions or making offsetting claims. This approach also requires those using carbon credits to carry out their due diligence and thereby ensure that only high-quality and transparent projects with strong social safeguards are chosen. Ultimately, however, any solution must respect the three core principles underpinning climate policy: the precautionary principle, the do no (significant) harm principle, and the primacy of emissions reductions.

## Efficiency of carbon dioxide removal

CDR efficiency refers to how much $CO_2$ is emitted from the activity (i.e. “leaked”) relative to the amount of $CO_2$ that is permanently stored over the life cycle of a CDR project. It is a metric that incorporates the risk of storage reversal, full value chain GHG emissions, storage permanence and storage capacity constraints.

CDR efficiency, as defined by *Chiquier et al.* is illustrated in the equation below. Here, leakage refers to the emission of GHGs along the supply chain and not just the physical leakage of $CO_2$ from storage.

$$\textbf{CDR efficiency} = \frac{\textbf{Amount of } \mathbf{CO_2} \textbf{ stored - } \mathbf{CO_2} \textbf{ leaked in supply chain}}{\textbf{Amount of permanent stored } \mathbf{CO_2} \textbf{ emissions}}$$

Both the technology and how it is deployed in each project will determine the efficiency for CDR over the project lifetime, including long-term carbon storage. CDR efficiency is strongly linked to the "carbon payback period" which is the length of time before a CDR system has permanently stored sufficient atmospheric $CO_2$ to compensate for the emissions released throughout all associated supply chains, particularly those relating to land use and land use change. This payback period is shorter if the physical removal of $CO_2$ happens immediately and rapidly, and associated GHG emissions are low (e.g. DACCS powered by additional renewable electricity).

The CDR efficiency over time is illustrated with indicative trajectories for different technologies and practices in Figure 4.

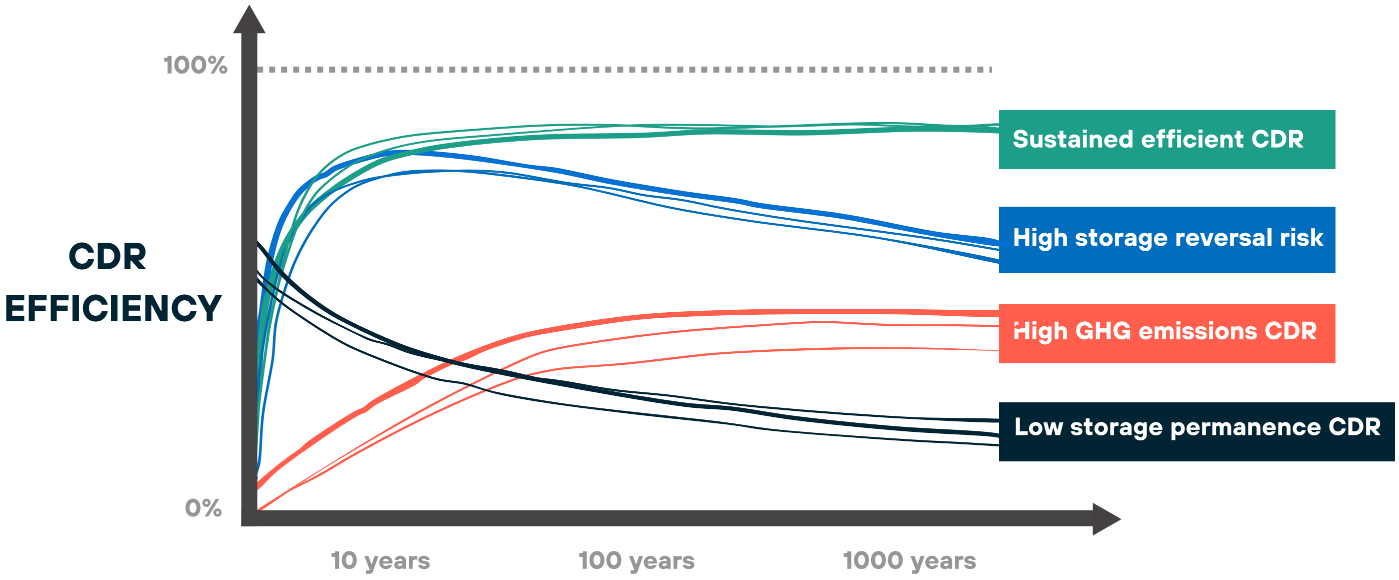
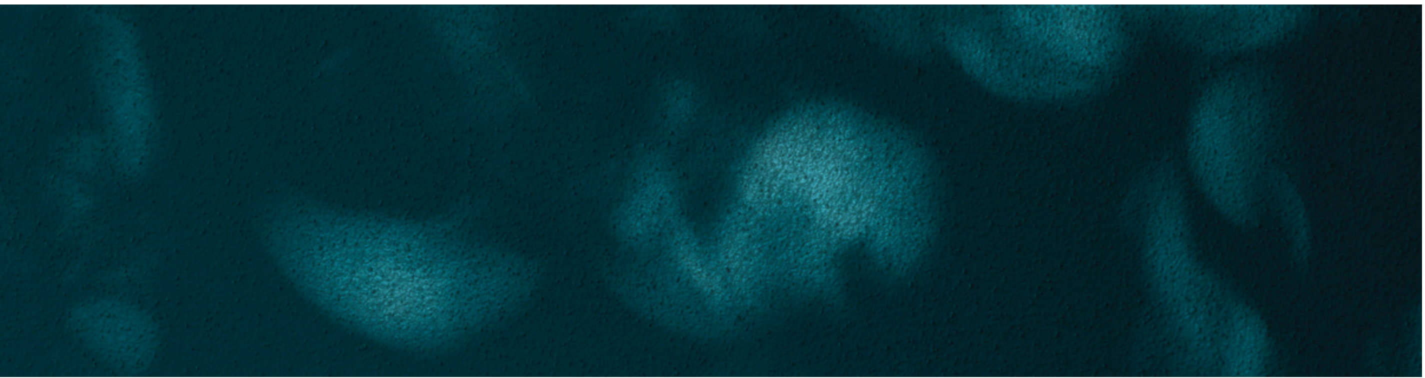


*Figure 4 CDR efficiency over time for a range of different CDR types, based on Chiquier et al. 2022.*



# Modelling

Different modelling approaches can be used to evaluate the potential and sustainability of CDR approaches. Each distinct model provides valuable information on realistic potentials from particular perspective. To interpret the results, it is important to understand the specific objectives of the models and the information that they can provide.

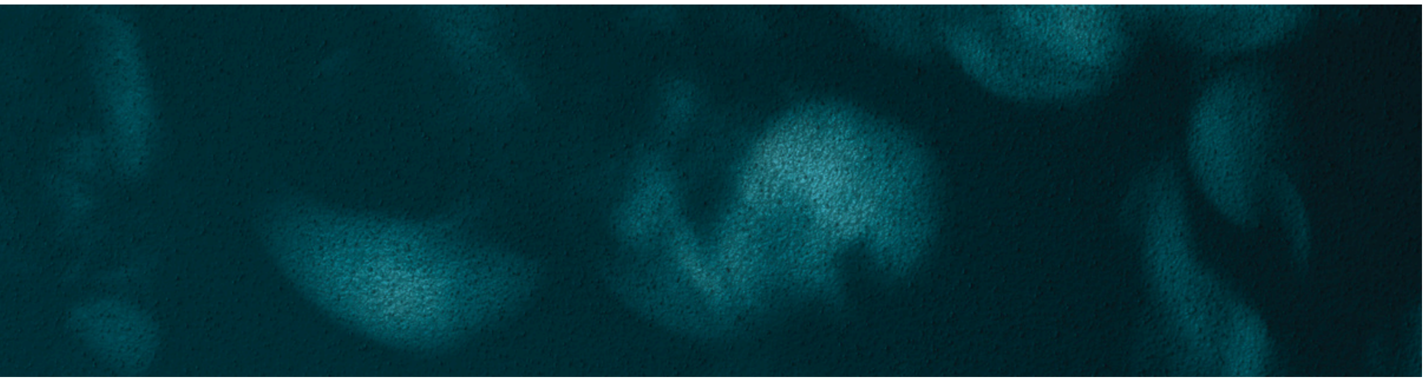
Below, three types of model analyses applied in the H2020 NEGEM research consortium are used to illustrate the specific information and potential limitations that each model approach generates.

**Life cycle assessment of environmental performance:** A life cycle assessment (LCA) is used to study a CDR project from a product or system perspective. It provides information on the environmental performance of the studied CDR approach over its life cycle with the most comprehensive system defined as from “cradle-to-grave". LCA can include several impact categories, and studies the impacts e.g. on climate, ecosystem, watersheds, air, resources, and human health. LCAs need to be made consistently to allow for effective comparisons to be drawn between the different CDR approaches.

When interpreting the results of any LCA study, the assumptions on the CDR process and the LCA methods applied need to be understood. These can be subjective yet affect the LCA outcome. Specifically, results of LCA studies on BioCCS can vary significantly due to different biomass feedstock, geographic location, process efficiencies, possible external energy sources used, and different system boundaries, in addition to indirect land use changes and feedstock substitution impacts.

**Integrated assessment models to analyse cost-optimised portfolios:** Integrated assessment models (IAMs) are used to find the lowest cost portfolio of CDR technologies required to meet a national, regional or global climate change mitigation target (e.g. 1.5°C warming) in different scenarios. These models are used to create the IPCC scenarios for climate change mitigation and often fall short of accounting for social and environmental constraints. Thus, they can be referred to as "demand-driven models". Most of the projections from these models show a high demand for BioCCS to achieve mitigation targets. One reason behind this is that models assume BioCCS to be a moderate cost solution as, in addition to the CDR achieved, energy can be generated throughout the process (e.g. BECCS). It also has a high technology readiness level compared to other (limited number of) CDR approaches included, such as enhanced rock weathering. However, the constraints on biomass supply included in the model are tailored by the user and may neither represent realistic or sustainable levels of supply nor acknowledge other environmental trade-offs such as pressures on planetary boundaries.

**Process-based biosphere model to assess environmental constraints:** A third category of models are process-based biosphere models used to assess environmental constraints in "supply-driven" approaches, such as the one used to study global biomass potential for BioCCS in NEGEM (LPJmL5-NEGEM). These models can assess CDR deployment from the supply side and provide detailed information on the availability of biomass resources when applying various restrictions i.e. by taking planetary boundaries into account. Supply-driven approaches can be applied using process-based biosphere models, which simulate the dynamics of both natural and agricultural ecosystems. They are designed to simulate and detect critical shifts in vegetation composition and distribution as well as stocks and flows of carbon, water, and nitrogen, in dynamic coupling and at a global scale.



## *Modelling approach (Kati Koponen, VTT) :*

| | **Life cycle assessment** | **Demand driven** *(e.g. IAMs)* | **Process-based biosphere model** |
|---|---|---|---|
| **Objective** | Compare sustainability performance of different CDR approaches on a per tonne $CO_2$ removed basis | Optimisation of the lowest cost portfolio of CDR technologies, to meet a national, regional, or global climate change mitigation target (e.g. 1.5°C warming) in different scenarios. For example, evaluate future need of selected mineral and metal demand for clean energy transition pathways, resource demands, bottlenecks in technology implementation due to resource scarcity. | Quantify sustainable biophysical potential of biomass-based CDR with feedstock production on uncultivated land and assess environmental pressures from rededicating pastureland to NETPs |
| **Assumptions** | Average parameters of a CDR approach used (not project specific data) | Assumptions on the energy system, CDR technologies, population and GWP growth, etc. | Biomass plantation coverage expands outside agricultural land without transgression of terrestrial Planetary Boundaries or rededication of pastureland to NETPs |
| **Major limitations** | Selection of specific CDR application pathways strongly influences the impacts in model output. Lack of standardisation means subjective selection of system boundaries to suit the user needs. | Assume a perfect foresight and market reactions, limited number of scenarios possible (e.g. 1.5°C, 2°C). Constraints may neither represent realistic or sustainable supply nor acknowledge other environmental trade-offs (e.g. planetary boundary impacts). In NEGEM scenarios, constraints from process-based biosphere modelling (LPJmL) were applied for BioCCS, biochar and reforestation. | Only biogeochemical assessment with no socioeconomic considerations, global technical efficiencies used (not project specific) |
| **Advantages** | Many different CDR approaches can be analysed on their emissions and resource use impacts across their entire lifecycle | Identification of cost-optimal pathways with multiple CDR approaches at both European and global levels, enables understanding on the scale of mitigation solutions needed and understanding on the energy transition and impact of CDR to energy demand | Simulates biomass growth and ecosystem impacts at both the global and local scale. |

# Monitoring, Reporting, Verification, Liability (MRVL)

Monitoring, reporting, and verification, followed by liability assignment (MRVL) are essential components of any carbon removal project that produces certified carbon removal units. MRVL ensures that the project delivers the removed carbon that they promise. MRV frameworks for national emissions inventory already exist, such as the IPCC Greenhouse Gas Guidelines. Defining best practice MRVL procedures and standards for the diverse range of carbon removal approaches is currently an area of active research.

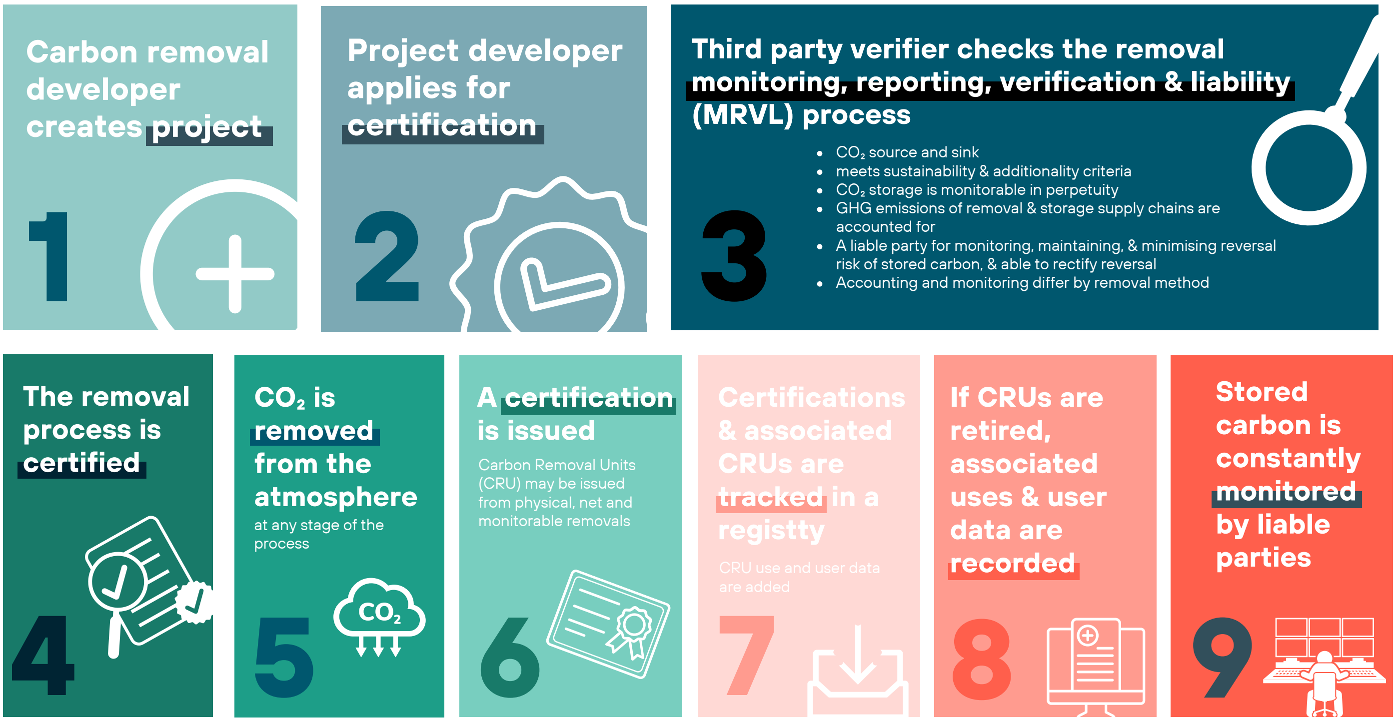


*Figure 5 "How to build a robust framework for the certification of high-quality carbon removals", reproduced with permission from Carbon Gap/Clean Air Task Force/Bellona.*

## Monitoring

Monitoring, also referred to as measuring, involves a robust quantification of the baseline flows of carbon, the additional carbon removed through the activity, monitoring of storage reservoirs, and of any associated GHG emissions in the value chain (see Step 4 in Figure 5 above, also "Accounting"). Developed methodologies should set out standardised measurement and monitoring guidelines for each type of CDR but may need adapting to the specific project.

Physical measurements of carbon stocks and fluxes should be prioritised for each deployment site to ensure monitoring is accurate for each specific project type and location and duration. Over time, model development and validation from field measurements can reduce the cost burden of physical measurement of all carbon stocks and flows for each defined time period.

For both physical measurements and model-based estimates, the associated statistical or empirical uncertainty should also be determined. This indicates how much the estimated amount of carbon removed may deviate from the real value. Ultimately, through improved understanding of carbon removal processes, and natural variability and more accurate assumptions in models, this uncertainty should decrease over time. The most conservative estimates should always be used, to minimise the risk of overestimating the removal value and to incentivise project developers to minimise the uncertainties.

## Reporting

Transparent and detailed communication of how the amount of carbon removed and stored was determined is a part of the MRVL process. Relevant information in the reporting process includes carbon flow and stock quantification uncertainty (empirical and statistical), quality control procedures, data sources and included assumptions, as well as a detailed description of the applied methodology.

## Verification

Verification is carried out by accredited, third-party auditors that belong to either public or private schemes. No conflict of interest may exist between the operator and the verifier; impartiality and independence must be guaranteed in order for the procedure to be credible. Once verified, certification is awarded, rendering the project eligible for carbon removal credits or units. It should be noted that, while the process of verification is not exclusive to carbon market mechanisms, it is a necessary step for certificates to be issued and thus increase trust in any system. Overall, verification is essential to avoid a misrepresentation of the amount of carbon removed. It attests to the accuracy and reliability of the data, guaranteeing the quality of a removal and bringing integrity to the system.

## Liability

Liability is required to guarantee responsibility over a particular removal or sequestration project, where carbon leakage or environmental damage occurs. Usually, liability falls on the operator, namely the entity carrying out the carbon removal or sequestration activity. This is because, following successful verification, operators benefit from the certification, and are consequently eligible for financial reward or support.

However, liability is often difficult to establish, especially when a removal process involves $CO_2$ being transported across borders before reaching the storage site, or when a particular removal facility is found not to be carbon-negative years later. In the latter case, the probability of a particular company or land manager addressing their carbon liability decades after the inception of the project is low. This results in future generations inheriting such responsibility; an unfair burden they did not sign up for and for which they received no financial compensation. Yet, someone must be held accountable for the released carbon, particularly considering the additional burst of $CO_2$ residing in the atmosphere as a result.

A solution is to block a certain amount of funds within a project, designated for potential leaks or storage site reparations. This is known as a “buffer pool”, and essentially acts as a safety net for unexpected losses. Unfortunately, these are rarely large enough to compensate for all the lost carbon and thus cannot be viewed as a fail-safe mechanism. Another option is for a transfer of liability to be foreseen once operations have ceased, rendering the new actor, either public or private, responsible for the damage.

In any case, adequate long-term frameworks for allocating responsibility are vital to address and manage risks, as well as increase trust in removal or sequestration projects. Depending on the nature of the reversal risk, different approaches to liability will be necessary, such that they are tailored to the reversal management that is required for that CDR approach. For example, a CDR approach requiring long-term maintenance to prevent carbon storage reversal, such as land management practices, will need a liability framework which incentivises the long-term management of that sink.

## Permanence

For carbon storage to be viewed as permanent, sequestered carbon cannot be re-emitted within a timeframe where it contributes to climate breakdown. Biogenic stores will likely fail to satisfy this permanence criterion due to inherent vulnerability to natural and anthropogenic disturbances, including the worsening impacts of climate change itself. As such, it may only have a limited reliability and capacity to tackle global warming even though it will be critical to address other significant environmental objectives, such as ecosystem degradation and loss of biodiversity.

There are various definitions of permanence in policy, voluntary carbon markets and scientific research. It is important to note that “real” permanence, in terms of indefinite storage spanning millennia, cannot be scientifically guaranteed, and using extremely long timelines to define permanence would effectively render the creation of carbon removals impossible.  A more nuanced time scale for permanence is therefore needed and should be understood as the time needed to keep carbon out of the atmosphere until humanity has either managed to halt climate breakdown and deal with its associated impacts. As such, a carbon removal can be viewed as permanent if the carbon stored is not released within a timeframe that allows it to aggravate climate change.

Storage duration is relevant for climate mitigation as $CO_2$ emissions are effectively permanent and primarily affect temperature outcomes on the basis of cumulative emissions. When $CO_2$ enters the atmosphere, approximately 15-40% of its carbon emission mass remains for over 1000 years, and about 20% remains for longer than 10,000 years. The rest of the carbon is taken up by ocean and land sinks (see on the "The carbon cycle") and completion of the absorption process takes several hundred thousand years. In stark contrast, most other GHGs have relatively short-lifespans and primarily affect temperature outcomes on the basis of emission rates. This extensive timeframe means that temporary storage, lasting anything between several years or several decades to a century, does not meaningfully contribute to climate action unless the same amount of carbon is continuously re-sequestered and managed. On the contrary, it delays emissions and can even exacerbate temperatures as the stored carbon will be re-released before climate stabilisation has been achieved.

Technical approaches presented in this handbook, such as DACCS and BioCCS can be considered permanent provided underground storage reservoirs are successfully sealed. Furthermore, mineral carbonation, the chemical reaction behind enhanced weathering has an expected storage time of more than 10,000 years. Stable fractions of biochar can be permanent, although there are still uncertainties in decomposition rates in different storage mediums. In agricultural applications, it will depend on the chemical composition of the biochar and the soil conditions to which it is applied. However, since the stored carbon in biochar and in enhanced weathering is diluted in the environment, eventually across reservoirs on land, and also in the ocean, over time, this makes the removed carbon difficult to track, and consequently to verify the permanence of the storage.

Meanwhile, land-based approaches that rely on biogenic stores (vegetation, sediments, soils) such as reforestation and soil organic carbon enhancement, likely only temporarily sequester carbon as they are vulnerable to natural or human disturbances such as harvests, land use change, pests, droughts, floods, and landslides. Many of these natural disturbances are likely to become more severe due to the impacts of climate change, with higher temperatures increasing the chances of carbon storage reversal.

Moreover, stored carbon is difficult to measure and quantify long-term, and saturation of the store will occur, reducing the effectiveness of the sink. Nonetheless, these approaches should not be discarded as, if managed and protected responsibly, they can store carbon over longer timelines, contribute a vital role in restoring biodiversity and help maintain ecosystem integrity as well as other so-called ecosystem services.

## Planetary boundaries

CDR deployment should contribute both to climate stabilisation and other crucial dimensions of planetary health, such as freshwater availability, nitrogen flows, and biosphere integrity. The Planetary Boundaries framework outlines the “safe operating space” for Earth system stability and can be applied to help define sustainability limits for CDR and identify key trade-offs. Analysis using this framework points towards significant potential trade-offs, in particular for biomass-based CDR approaches given their CDR efficiency, required land area, and impacts on planetary boundaries. Nevertheless, reforestation can provide substantial synergies between climate change mitigation and international targets for nature restoration (i.e. the Kunming-Montreal Global Biodiversity Framework).

# What are planetary boundaries?

Planetary boundaries define the “safe operating space” for human activity within different Earth system processes. This reflects the functioning of a stable Earth system from the Holocene geological epoch that covers the past 11,700 years. Once a boundary threshold is transgressed, there is a risk of catastrophic, large-scale environmental change, as critical transitions, spillover effects, and tipping points may be reached.

Researchers have identified nine processes that are “critical for maintaining the stability and resilience of the Earth system as a whole”. The Planetary Boundaries Framework considers the systemic impact of these nine interconnected processes on the complex Earth system, enables human interference to be quantified, and for any changes to be monitored over time. Quantification is possible for individual boundaries, but the interaction and combined response between boundaries is an area of active research.

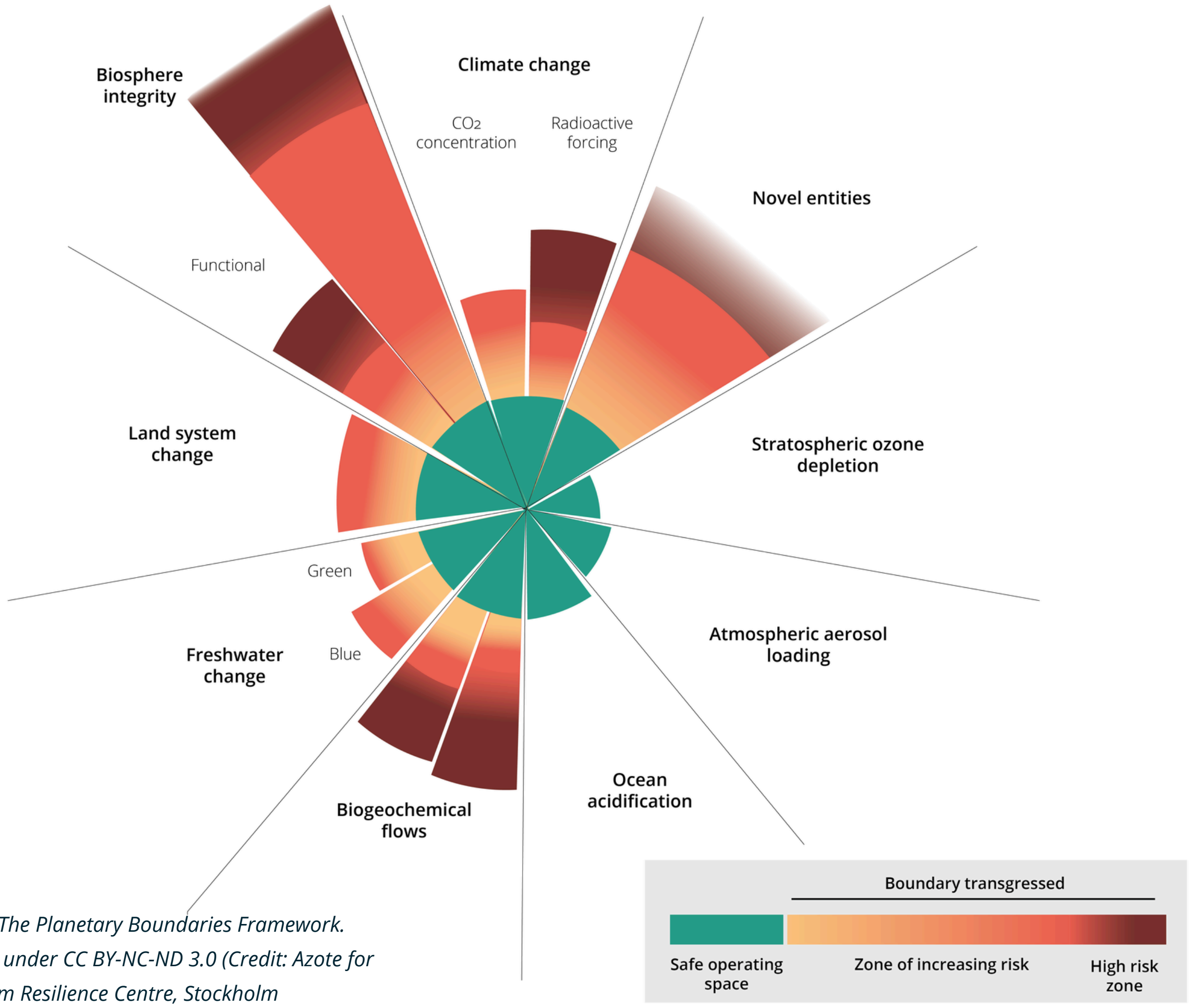


*Figure 6 The Planetary Boundaries Framework. Licenced under CC BY-NC-ND 3.0 (Credit: Azote for Stockholm Resilience Centre, Stockholm University).*

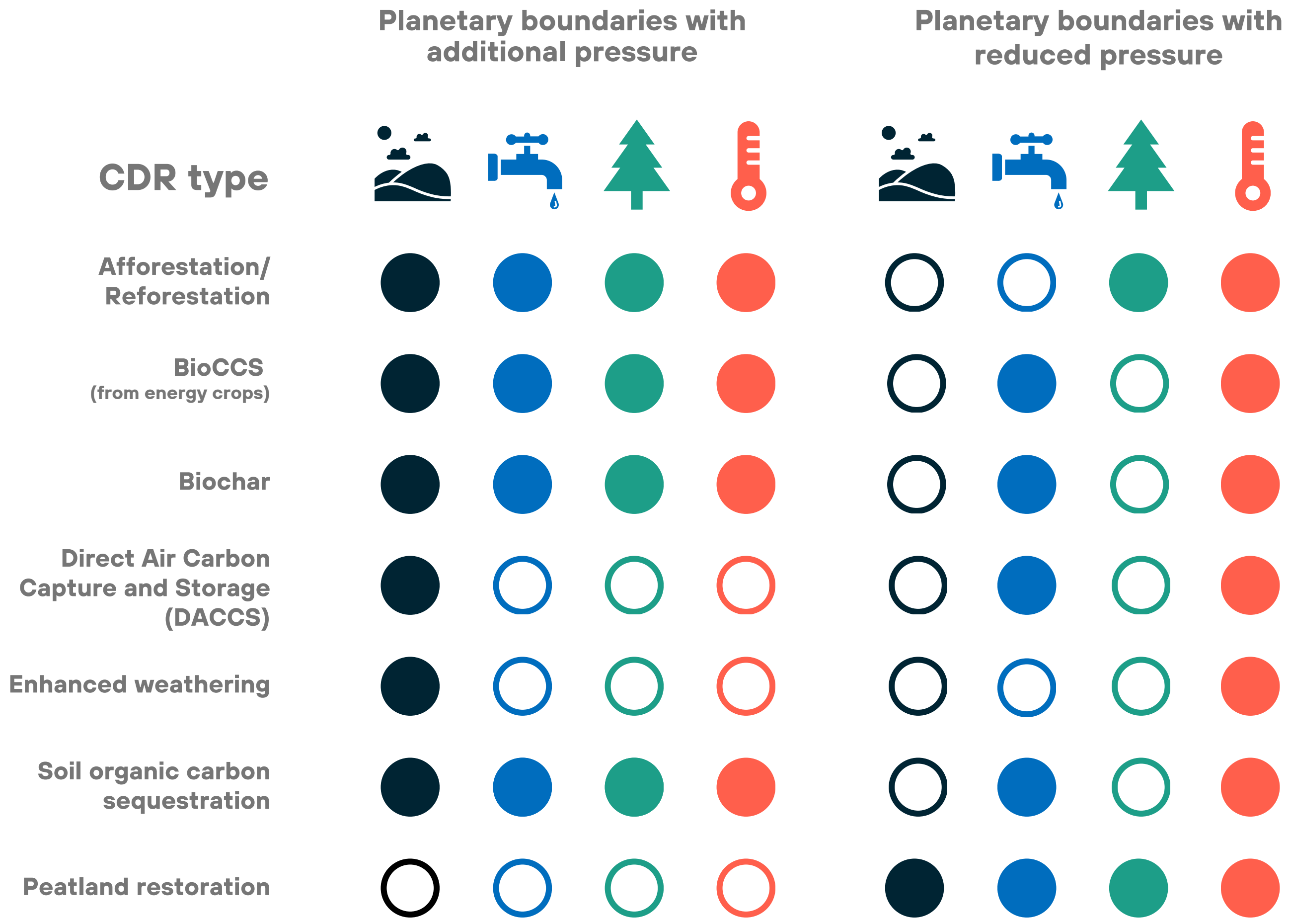
There has been considerable interest in applying this framework in environmental policies and governance strategies as this concept also strongly links to sustainable development. There is some interest in using the framework to evaluate a nation's contribution to a resilient Earth System. The Doughnut theory of Economics adds human well-being dimension to the core of the safe operating space, with the ecological ceilings provided by the planetary boundaries concept. A prosperous economy is detailed as one which meets the twelve social foundations (such as energy, water, food, health, housing) while remaining below the ecological ceilings.

## Why are planetary boundaries relevant for CDR?

Currently, the climate change planetary boundary is transgressed, placing us in a zone of increasing risk. Atmospheric global monthly mean $CO_2$ concentrations reached 421 ppm in December 2023, exceeding the planetary boundary of 350 ppm.

By removing and permanently storing carbon, CDR may relieve some of the pressure on the climate change planetary boundary. However, each approach to CDR has potential trade-offs from the natural resources that are needed in their deployment (see also Figure 6). For example, additional land area, harvesting of terrestrial biomass, extraction of minerals/metals, may all exacerbate pressure on other planetary boundaries such as land-system change, biosphere integrity and nutrient (biogeochemical) flows, that are already under immense pressure. Trade-offs on some level may be unavoidable, but ideally a systemic impact assessment for each CDR project should ensure an overall climate benefit that does not jeopardise other aspects of sustainability and environmental protection. Some CDR types can both increase and decrease pressure on planetary boundaries due to different impacts.

For the sake of simplicity, Figure 6 does not provide exhaustive indication of planetary boundary impacts but demonstrates that CDR activities will impact planetary boundaries differently and potentially in opposing directions even for one project. NEGEM work indicates that most biomass-based approaches reduce the net pressure.



| CDR type | Planetary boundaries with additional pressure | | | | Planetary boundaries with reduced pressure | | | |
|---|---|---|---|---|---|---|---|---|
| | 🏞 | 🚰 | 🌲 | 🌡 | 🏞 | 🚰 | 🌲 | 🌡 |
| Afforestation/ Reforestation | ● | ● | ● | ● | ○ | ○ | ● | ● |
| BioCCS<br>(from energy crops) | ● | ● | ● | ● | ○ | ● | ○ | ● |
| Biochar | ● | ● | ● | ● | ○ | ● | ○ | ● |
| Direct Air Carbon Capture and Storage (DACCS) | ● | ○ | ○ | ○ | ○ | ● | ○ | ● |
| Enhanced weathering | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● |
| Soil organic carbon sequestration | ● | ● | ● | ● | ○ | ● | ○ | ● |
| Peatland restoration | ○ | ○ | ○ | ○ | ● | ● | ● | ● |

*Figure 7 Potential interaction between CDR project types and planetary boundaries indicating potential trade-offs and co-benefits of each activity. Brown icon = land system change, Blue icon = freshwater use and nitrogen flows, Green icon = biosphere integrity (net primary production + biodiversity), Red icon = climate change (atmospheric $CO_2$ + radiative forcing).*

The NEGEM project used the Planetary Boundaries Framework to indicate the potential of NETPs to remove carbon in a manner which is conscious of the Earth systems' complexity. This means that further transgressions of planetary boundaries are avoided, and remaining regional opportunities within the safe operating space are utilised.

As stated in the NEGEM project: "This global perspective on Planetary Boundaries should be carefully considered for developing CDR strategies in the European Union, as it is likely that European CDR demands can only partially rely on sequestration on its own territory. Assumptions about realistic CDR potentials within and beyond EU territory should thus be founded on careful consideration of all Planetary Boundaries, not just the climate targets."

# Separation of activities and the need for separate targets

Climate mitigation policy covers a number of activities, namely emission reduction, emission avoidance, permanent carbon removal, and land-based sequestration. Separate activities require separate targets. Certain NETPs have the potential to contribute to more than one activity. This section seeks to explain each activity, provide a rationale for separation, and illustrate the various problems that conflating targets and activities can cause.

## What is meant by separation of activities?

The activities can be defined as follows:

**Emission reduction:** the quantified decrease in GHG emissions related to or arising from an existing activity between two points in time, in a process that contributes to decarbonisation (Figure 9). It involves multiple actors, and must be enforced on company-, sector-, regional- and national-levels.

**Emission avoidance:** the displacement or prevention of future, expected GHG emissions. Examples include renewable energy projects and energy efficiency measures. Avoided emissions are frequently recorded in emission reductions, which has led to confusion between both terms. Projects can lead to both emissions avoidance or reduction, and the dividing line between both is not always crystal clear for stakeholders. However, both activities lead to fewer GHG entering the atmosphere (Figure 8). For the foreseeable future, this is the most important type of action that will tackle climate change. The goal is to reach a slower increase or to stop increasing atmospheric levels $CO_2$.

**Permanent carbon removal**: the physical removal of existing carbon dioxide from the atmosphere, which is permanently stored, for example in geological reservoirs or through mineralisation. NEGEM work (see Section "Accounting") and the EU's Carbon Removal Certification Framework (see Section "Status of EU legislation and policy") view permanence as a period lasting at least several centuries. DACCS, BioCCS and enhanced weathering fall under this category. The climate action is physically extracting and permanently storing $CO_2$ out of the atmosphere (Figure 8) and the result is slowing the increase in atmospheric $CO_2$ levels, balancing out remaining emissions in a "climate neutrality" state, and decreasing atmospheric $CO_2$ levels thereafter.

**Sequestration in natural sinks:** the physical absorption of carbon dioxide from the atmosphere, that is stored in natural biological reservoirs such as vegetation, sediment or soils. These reservoirs can be highly vulnerable to reversals and are often in direct contact with the atmosphere so any re-emitted carbon will directly contribute to warming**.** These reservoirs are often in direct contact with the atmosphere so any reemitted carbon will directly contribute to warming. This category covers afforestation, reforestation, and soil organic carbon sequestration, also known as "land sinks". Marine biomass and blue carbon are equivalent natural sinks in the ocean.

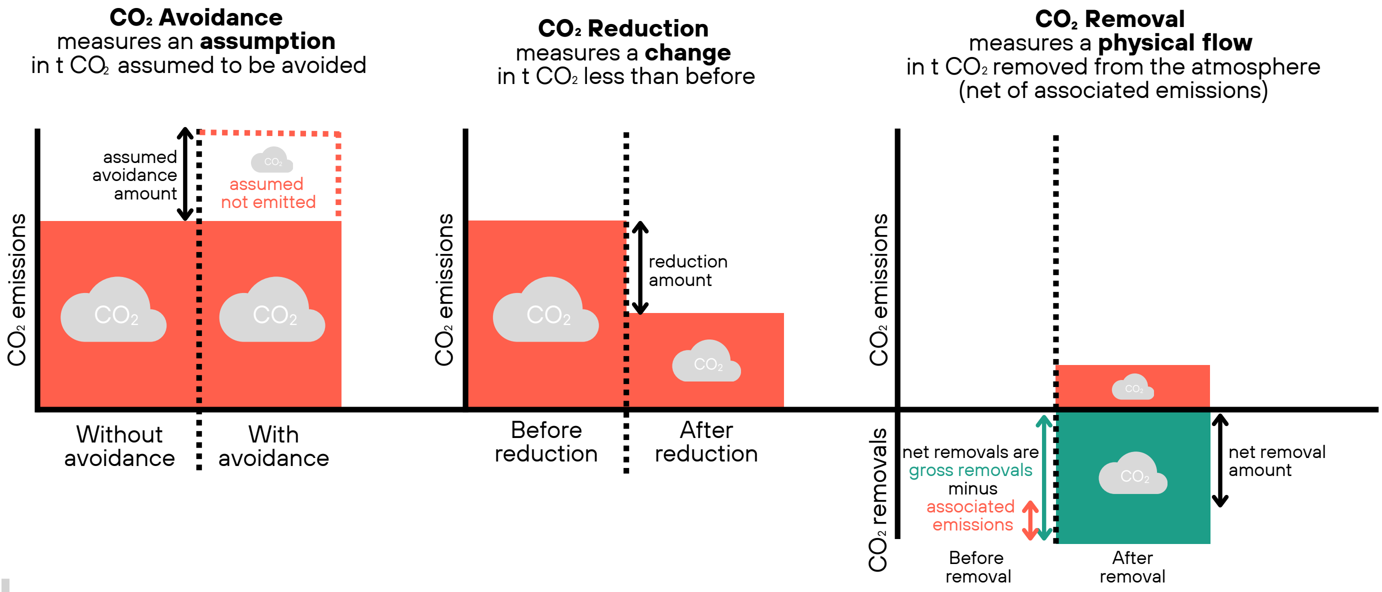


*Figure 8 Difference in net emissions between an avoided emission (left), reduced emission (centre), and a carbon removal (right). Source: Bellona.*

Note that certain NETPs have the potential to contribute to more than one activity. However, there is a hierarchy in climate action that must be respected if we are to effectively solve the climate crisis. Emission reduction and avoidance must always be the absolute priority as they have a certain and permanent impact on limiting atmospheric concentrations, which is critical to reducing the severity and impacts of the climate crisis.

Meanwhile, permanent removals can supplement reductions and help mitigate climate change by potentially keeping emitted carbon away from the atmosphere for centuries to millennia, balancing residual emissions, and eventually, leading to a net negative scenario. Investments and policies aimed at their safe and sustainable deployment are needed. However, attention to the potential of permanent removals must not divert efforts from slashing emissions. This is particularly true considering the technological constraints, substantial resource requirements, possible negative environmental and social impacts, and lesser climate effect compared to not emitting in the first place. Additionally, they remain uncertain, are costly, and their large-scale deployment in the near future remains unlikely.

As for land-based sequestration, it can play a vital role in protecting biodiversity and restoring ecosystems if enhanced through nature restoration activities. Nonetheless, it cannot be considered a permanent form of carbon storage as it is vulnerable to natural and human disturbances and thus prone to leakage. Furthermore, those vulnerabilities are highly likely to be exacerbated by the impacts of the climate crisis itself, along with increasing the risk of loss from existing terrestrial stores. In terms of impacts on GHG atmospheric concentration, land-based sequestration would struggle to counterbalance historical land use emissions because it effectively requires reforestation of all previously deforested land. Hence, removing and storing fossil carbon from the “slow” carbon cycle in land-based sinks retains more carbon in the vulnerable and active part of the carbon cycle (“fast cycle”). Returning emitted fossil carbon to permanent sinks mitigates this higher risk of catastrophic storage reversal.

## Why are separate targets relevant to CDR?

In light of the different activities and their varying contributions to the environment, it is important to establish separate targets for emission reductions, permanent removals, and sequestration in the land sector. Separation provides many benefits:

**Avoiding the slowing down or delaying of emission reduction efforts, also known as mitigation deterrence.** Different activities cannot act as a substitute for one another; they are not interchangeable - a removal can never meet reduction obligations, and overreliance on these is risky. As such, it is better to think of removals as a supplement to urgently needed reductions. In this sense, establishing a clear separation maximises the contribution of each activity by enforcing action on all fronts.

**Allowing policy to focus on the specific activity.** Each activity plays its own role in climate action, with emission reductions being the key player in limiting global warming, land-based sequestration providing excellent co-benefits, and permanent removals extracting residual emissions in hard-to-abate sectors.

**Avoids equating geological storage and biological sinks thereby preventing misuse or misclassification of vulnerable or temporary storage as "permanent removals".** This is particularly relevant to combating false climate neutrality claims and to guaranteeing environmental integrity.

**Provides transparent accounting, measurable indicators, stronger governance frameworks, increasing certainty, trust and transparency.** This will also prevent exaggerated estimations of future contributions of negative emissions in climate models and favour an honest assessment over the amount of time and investment needed.

The EU has set net targets for GHG emissions reductions for 2030 (55%) and 2050 (net-zero) in comparison to 1990 levels. Note that the EU's "net" targets combine emission reductions, removals and sequestration into one number, failing to distinguish between each activity.

This is exemplified in the European Commission's 2040 climate target communication which has suggested a net 90% target. This target might at first glance appear to aim high, but it actually implies an emissions reduction target (gross target) of 82% at maximum. The remainder of the net 90% consists of temporary storage (some of which is very vulnerable such as soil carbon sequestration) and permanent removals. Furthermore, the 2040 strategy, calls for an annual removal or sequestration target of up to 400 Mt carbon dioxide equivalent by 2040, without unpacking or disaggregating this goal in the communication itself. This conflates permanent removals and storage in soils or biomass, despite having very different impacts on the climate.

## Status of EU legislation and policy

Relevant EU legislation for CDR and natural sequestration includes: the European Climate Law; the Carbon Removal Certification Framework; the Land Use, Land Use Change and Forestry Regulation, the Nature Restoration Law and the Common Agricultural Policy.

The Carbon Removal Certification Framework is the first EU instrument to directly tackle carbon dioxide removals.

Currently, EU legislation contains several loopholes and lacks ambition. Amongst other issues, it does not provide for separate targets and misses critical elements that would enable sustainable scaling up of carbon removals.

## European Climate Law (ECL)

Published in July 2021, as part of the European Green Deal, the European Climate Law set two binding targets: cutting net GHG emissions by 55% compared to 1990 levels by 2030, and reaching climate neutrality by 2050, with the aim to achieve net-negative thereafter. The ECL instructs EU institutions and member states to "prioritise swift and predictable emissions reductions and, at the same time, enhance removals by natural sinks" with the contribution of net removals to the 2030 target being limited to 225 Mt $CO_2$ equivalent.

The text also states that the EU shall aim to achieve a higher volume of removals in 2030, to support the objective of achieving climate neutrality by 2050. Nonetheless, the Law does not mention permanent removal technologies. It also fails to address or define the role removals and natural sinks should play to reach climate neutrality, does not set interim targets (besides the 2030 target for emission reductions and land sinks), and does not delve into the topic of residual emissions.

## Certification framework for permanent carbon removals, carbon farming and carbon storage in products (CRCF)

The CRCF is a policy that is globally unique. It is a certification scheme for EU projects across a wide range of activities. There are four main activity groups, each with their own unit: (1) emission reductions from soils (including agricultural soils); (2) enhanced natural sinks in soils and forests; (3) carbon storage in products lasting at least 35 years; and (4) permanent carbon removals that last at least several centuries.

The certification scheme was agreed upon in Spring 2024 - though at time of writing it has not been formally approved. It is voluntary, which means countries, companies and land managers can choose whether or not to use it. The CRCF itself only sets the basic rules on how the overall scheme should function once fully operational. These rules include definitions for key concepts, a basic formula for quantifying the net-benefits of the various activity-types, basics for the functioning of the scheme and some guidelines on liability and environmental sustainability criteria.

The stated goal of the CRCF is to scale up carbon removal activities in the EU. While this is indeed necessary, the CRCF framework lacks critical elements to enable this to happen sustainably. For example, not all emissions are accounted for when quantifying the “net-benefit” of a project, potentially unambitious standardised baselines are to be used, and social sustainability safeguards have been excluded from the framework. Most importantly, it barely scratches the surface in determining what the various units generated by certified activities are to be used for.

The only “use case” decisions that have been made for CRCF units is that they cannot be used for international compliance schemes’ (i.e. CORSIA) or for the Nationally Determined Contributions under the Paris Agreement (NDC) of non-EU countries.

While all CRCF units are intended to be counted towards the EU NDCs, they can also be used globally to offset emissions in voluntary carbon markets. However, double counting between the EU’s climate targets and voluntary carbon markets has not been addressed. This approach risks double counting between EU policies and GHG inventories, and companies using CRCF units for compensation claims in or outside the EU.

The Regulation itself is relatively short as most of the detailed decisions to operationalise it will follow in Delegated Acts (DAs), to be prepared by the European Commission over the coming years. These DAs will cover a broad set of issues, including the establishment of a CRCF registry, but crucially, the specific methodologies project developers must adhere to, like how to quantify the net-benefits of their projects, address liability for potential reversals and measure and tackle sustainability impacts.

## Land use, land use change and forestry (LULUCF) Regulation

The LULUCF Regulation sets targets for the EU to reduce emissions and increase sequestration in the land use and forestry sectors, such as in forests, management of cropland, grassland, and wetlands by 2030. As part of the overall revision of the EU’s 2021-2030 climate policy and targets, the Regulation was reformed in 2023. The revision set a new absolute target at EU-level for net removals of 310 Mt of $CO_2$ equivalent, from 2026 until 2030. This will be supported by relative national targets defined for each EU country based on previously reported net removals data. However, these can still be adjusted by member states (for instance by changing the method of calculation and impacting its national relative target) and tend to vary significantly across the bloc. While the LULUCF regulation does not refer to CDR *per se,* it defines a sink as “any process, activity or mechanism that removes a GHG, an aerosol, or a precursor to a GHG from the atmosphere”.

The revision also seeks to improve the MRV of emissions and removals through the use of remote sensing. Moreover, it established comprehensive accounting rules with varying benchmarks and reference years attached to each land type. Sequestered $CO_2$ is recorded as a removal, whereas the removal of biomass, organic matter, and interference in the ecosystems resulting in a release of previously captured emissions are classified as emissions.

As for harvested wood products, these are accounted as part of the LULUCF sector’s carbon stock. Each product is assigned a corresponding decay factor - despite the lack of control over the actual life cycle of the wood products - to determine how long products can remain within the LULUCF sector’s carbon stock. Once this period has expired they proceed to be automatically accounted as emissions.

Lastly, some flexibility mechanisms were included and can potentially reduce the overall EU-wide target in 2030. Flexibilities also allow countries that have a surplus of net removals to receive LULUCF credits, which can, among others, be traded with countries that have failed to meet their targets. Up to 262 million tonnes of $CO_2e$ sequestered in the LULUCF sector can be used from 2021-2030 to offset emissions under the Effort Sharing Regulation (ESR). This covers emissions from a wide range of sectors, including road transport, buildings and agriculture. This flexibility mechanism undermines environmental integrity as it allows biogenic $CO_2$ sequestration to be used to offset fossil emissions under the ESR targets - delaying much needed climate action in those important sectors. It also ignores the large degree of uncertainty surrounding measurements under the LULUCF Regulation and establishes a false equivalence between emission reductions and sequestration in the land sink.

## Nature Restoration Law (NRL)

Proposed in June 2022 and finalised in February 2024, the NRL is a key component of the EU Biodiversity Strategy, which calls for binding targets to restore degraded ecosystems, in particular those with the most capacity to sequester carbon. Despite a meagre 15% of European ecosystems being in “good” condition, the NRL only aims to restore at least 20% of the EU's land and 20% of sea areas by 2030, with priority given to degraded habitats located in Natura 2000 sites. Member states must also restore at least 30% of habitats specifically covered by the new law from a poor to a good condition by 2030. That target would increase to 60% by 2040, and 90% by 2050.

The NRL received significant backlash and was subject to an aggressive misinformation campaign that almost led to its demise. Amongst others, it was labelled as a threat to the agricultural sector and food security. Consequently, its ambition and contents were significantly watered down compared to the original Commission’s proposal and the Council’s position. For instance, the Commission’s text proposed an ambitious target for the restoration of drained peatlands under agricultural use, fixing a minimum share of rewetting. This target was later reduced, both for the restoration of drained peatlands used in agricultural purposes and in the mandatory share of rewetting. In addition, provisions on the restoration of agroecosystems can now be temporarily suspended where targets are deemed to severely reduce the availability of land needed for sufficient food production for EU consumption. As such, the law lacks ambition in terms of addressing the current biodiversity crisis and restoring degraded ecosystems.

In February 2024, the NRL was adopted by the European Parliament with 329 votes in favour, 275 against and 24 abstentions. After several postponements, the Law was finally approved by the European Environmental Ministers Council in June 2024.

## Common Agricultural Policy (CAP) 2023-2027

Launched in 1962, the CAP is one of the EU’s oldest policy instruments. It has since undergone several reforms, the most recent in December 2021, following the adoption of the European Green Deal. The CAP is divided into two pillars. The first involves the direct payments linked to conditionality rules, specifically, the fulfilment of statutory management requirements from EU law, and of nine “good agricultural and environmental conditions” (GAECs). These GAECs include, amongst others, maintaining permanent grassland, protecting wetlands, managing water, and preventing soil erosion. Member states are responsible for translating these high-level criteria into national and regional standards.

In addition to improving the conditionality regime, the 2023-27 reform introduced the so-called “eco-schemes”, which are designed to incentivise sustainable farming practices, such as those falling under the term “carbon farming”. Carbon farming broadly describes farming practices that result in emissions reductions or carbon sequestration. This encompasses agroforestry, use of catch crops, cover crops and conservation tillage enhancing soil organic carbon, and restoration of peatlands and wetlands. The eco-schemes are voluntary, allowing farmers to opt in or out on an annual basis and change the chosen practices yearly, with 25% of the total direct payments being allocated to these for the 2023-27 period.

The second pillar focuses on the EU’s rural development policy and agri-environmental-climate measures (these are similar to eco-schemes and can span over multiple years). In comparison to the first pillar, the second pillar offers a higher degree of flexibility, allowing regional, national and local authorities to formulate their individual multiannual rural development programmes. Its programmes are co-financed by European Agricultural Fund for Rural Development, regional or national funds.

Lastly, the 2021 reform introduced the new obligation for EU countries to detail their intended climate ambitions and set out how they would achieve CAP objectives in the so-called national CAP strategic plans. This grants member states autonomy when implementing objectives, in accordance with national conditions and needs.

Since its inception, the CAP has funded climate damaging practices such as intensive livestock rearing or farming on drained peatlands. It prioritises increasing productivity at the expense of the environment, producing cheap commodity crops and animal products for the food industry and export markets. Indeed, the 2014-2020 period dedicated one-quarter of the CAP budget (€100 billion) to climate action, yet this had a minor impact on agricultural emissions, as the potential success of the conditionality criteria was severely overestimated. Eco-scheme uptake has also failed to meet expectations and the European Court of Auditors recently concluded that the CAP Strategic Plans are not well-aligned with the Green Deal goals and targets, with key elements for assessing CAP green performance missing.

In addition, direct payments continue to be disbursed as untargeted farmer income, with conditionality standards being very loosely defined. So far, the Commission's response to the crisis has been to water down green provisions in the CAP. Unfortunately, this fails to meet many of the farmer's concerns, chief among them, farm income support and concerns about competitiveness in the international market.

## In the pipeline

In November 2023, the Commission put forward a Proposal for a Regulation on a monitoring framework for resilient European forests, as part of its EU Forest Strategy. The proposal aims to plug information gaps on European forests and provide comparable, consistent, and detailed data on the status of forests. This will allow EU countries, forest owners and forest managers to improve their response to growing pressures on forests and strengthen forest resilience. The proposal also aspires to offer better data and knowledge for policymaking and implementation, including up-to-date information on natural disturbances and forest disasters.

Considering that 60% of European soils are degraded, in July 2023 the Commission tabled a Proposal for a Directive on soil monitoring and resilience ("Soil Monitoring Law"), in line with the Soil Strategy, with the ultimate objective for all soils to be in a healthy condition by 2050. The proposal provides a definition on soil health, presents a monitoring framework, lays down rules on sustainable soil management, and requires EU countries to identify and investigate potentially contaminated sites, as well as address unacceptable risks for human health and the environment.

# Approaches to carbon dioxide removal

Carbon dioxide can be removed using many different capture processes (biological, geochemical, synthetic) and stored in a variety of reservoirs (Figure 10). All CDR systems are heterogenous and implementation-specific, resource and energy intensive, require long-term management, robust monitoring and verification frameworks.

All CDR systems will be more effective the more efficient the supporting resource use is (e.g., transport, energy generation, biomass cultivation). Hence, each CDR system (i.e. CDR deployment type and location) will have advantages and disadvantages due to different required resources.

A balanced deployment portfolio of technologies and practices will ideally minimise the system impacts of CDR and planetary boundary impacts, while maximising the physical removal of carbon and aligning with other sustainability goals and adhering to social and physical credibility principles. Within the NEGEM project, sustainability, technical and economic constraints on potential CDR portfolios were assessed using a variety of modelling approaches (see also "Modelling"), including at the EU member state level.

The following six factsheets aim to describe a technology or practice that could be used to remove and store carbon, indicating sustainable potentials, advantages, and caveats. These factsheets are not an exhaustive list of NETPs, as indicated in Figure 10, but focus on those most intensely studied within the NEGEM project. Technical performance indicators are provided at the top of each factsheet. Further information, including relevant constraints, have been determined using existing literature, such as the State of CDR report, and through expert consultations within the NEGEM consortium.

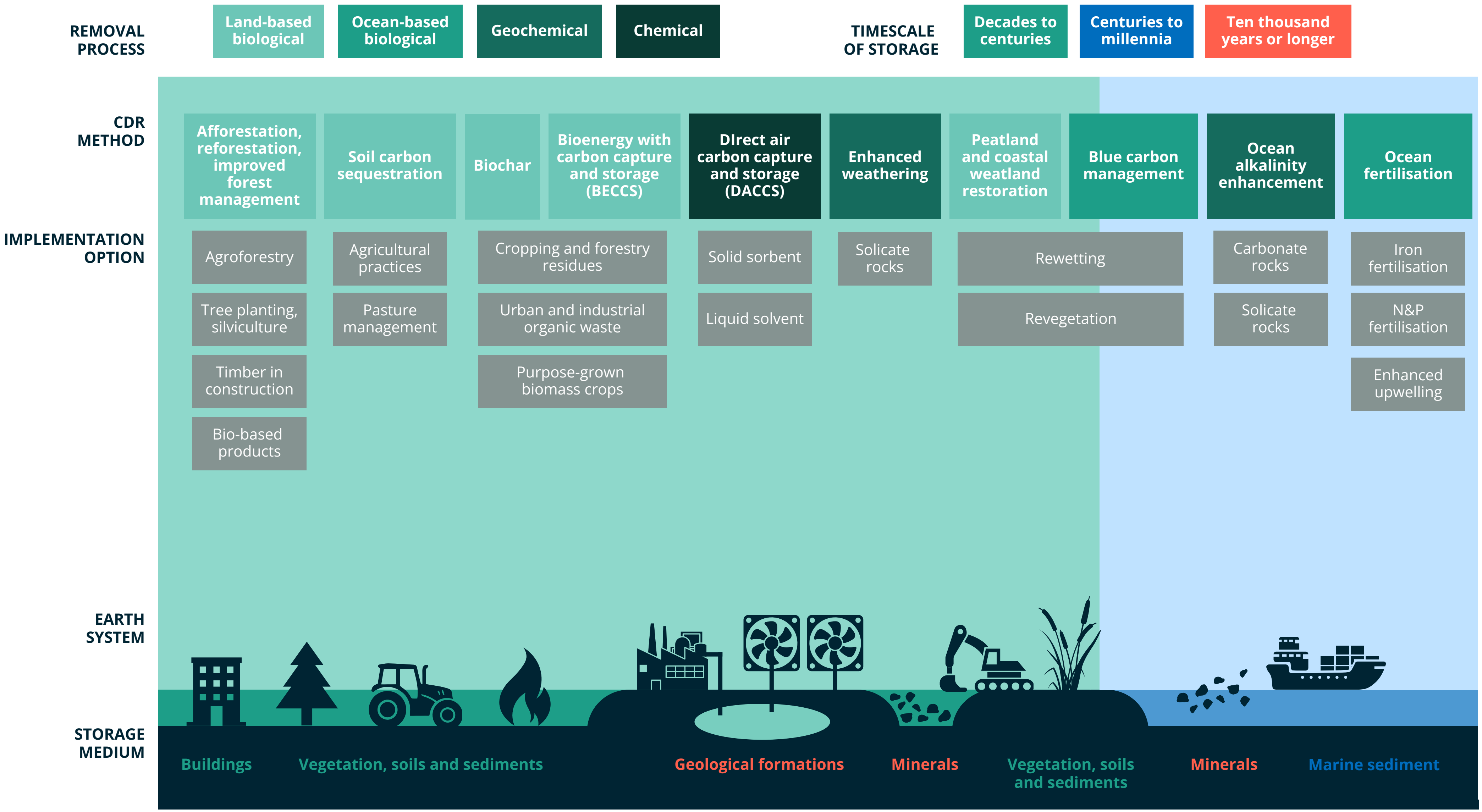


*Figure 9: Overview of carbon removal approaches, processes, and carbon storage types for a range of NETPs. Source: IPCC AR6 WGIII Chapter 12, Box 8, Fig. 1*

A brief explanation of the technical indicators is provided here:

- **Expected permanence** refers to the anticipated storage stability of the carbon in the particular storage reservoir (geological, biological, (geo)-chemical).

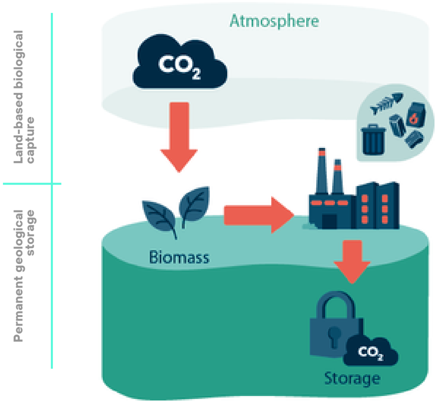
- **Reversal risk** refers to the risk that carbon could be lost or leak from the storage medium.

- **The uncertainty in the amount of initially captured carbon** indicates how accurately the amount of carbon captured can be measured. Indirect measurements and complex feedstock supply chains increase this uncertainty.

- **The uncertainty in the amount of carbon stored over time indicates how accurately the stored carbon can be monitored over time.** Dispersed carbon storage such as in enhanced weathering or biochar, where material is applied to an open ecosystem is practically impossible to track using only direct measurements. These are also more uncertain than systems involving geological storage.

- **The ease of MRV indicates** how easy it is to measure, report and verify the amount of carbon stored over time. Low indicates difficult MRV, whereas high indicates less challenges to fulfil MRV requirements. MRV protocols already exist for many approaches.

- **Key benefits** listed are limited to environmental or ecosystem co-benefits, in addition to co-production of energy or other fuels from the CDR approach.



# BioCCS

A process that can remove carbon or reduce $CO_2$ emissions

| | |
|---|---|
| Expected permanence | millennia |
| Reversal risk | low |
| Uncertainty in amount of initially captured carbon | medium |
| Uncertainty in amount of carbon stored over time | low |
| Ease of MRV | high |
| Key co-benefits | Energy production (heat, electricity, fuels) |

## Advantages

### € CHEAP RETROFITTING

CCS can be applied to existing point sources of biogenic $CO_2$, such as paper mills, ethanol plants and biomass power/CHP plants. This makes it cheaper, whilst contributing to energy security.

### PERMANENT STORAGE

Sequestered carbon is stored permanently with low risk of reversal.

### MRV

Protocols for monitoring, reporting and verification already exist.

### PRODUCTION OF USEFUL BY-PRODUCTS

Energy in the form of heat, electricity or fuels are produced during the biomass conversion. This decreases the energy footprint of BioCCS and can offer additional revenue streams.

## What is BioCCS and how does it store carbon?

Biomass with carbon capture and storage (BioCCS) converts the $CO_2$ sequestered in biomass into energy, fuels, or other uses. The carbon released during this process is captured and stored in permanent geological storages. The selected biomass source and conversion pathway differ depending on the BioCCS project at hand, which in turn influences the CDR potential. The biomass source may be forest or agricultural residues, pulp and paper industry, wood pellets, solid municipal waste or dedicated crops, whilst conversion pathways involve biological or thermochemical processes. In this sense each BioCCS plant is unique, involving a specific feedstock, supply chain, $CO_2$ capture process and downstream processes.

Biomass used in BioCCS is often “zero-rated” meaning the carbon the biomass captured while growing is considered to be emitted upon harvest (accounted for under LULUCF emissions accounting). Any biogenic $CO_2$ captured from biomass conversion in a BioCCS plant is automatically considered a negative emission. Existing point source biogenic $CO_2$ emissions can also be captured.

There are currently 19 bioenergy production facilities around the world either in operation, piloting or under construction. Some prominent projects in the field include Drax and Stockholm Exergi with the intention of capturing 8 Mt $CO_2$/yr and 0.8 Mt $CO_2$/yr respectively followed by permanent geological storage.

Relevant regulatory frameworks: Biomass feedstock sourcing should comply with EU Renewable Energy Directive guidelines for sustainable biomass.

## Challenges

### HIGH VALUE CHAIN EMISSIONS

Long distances between biomass source, processing and storage sites result in higher emissions along the entire value chain.

### IMPERFECT CARBON CAPTURE RATES

Not all carbon from bioenergy conversion can be directly captured (capture rates ca. 90-99%).

### PLANETARY BOUNDARY PRESSURE

Large-scale deployment from dedicated bioenergy crops severely conflicts with planetary boundaries and biodiversity goals. Biomass crops require vast amounts of water, fertiliser and land, competing with food security, whilst raising food prices.

### % LONG CARBON PAYBACK TIMES

Carbon debt payback time can be long depending on biomass source.

### HIGH INDIRECT GHG EMISSIONS

Associated deforestation and indirect land-use change emissions can be high. Since the demand for food and feed crops remains, more food and feed is produced elsewhere and just displaces where emissions occur.

### LEAKAGE POTENTIAL

Potential leakage during biomass transport, particularly if biomass used and produced in different regions.

# What is the sustainable potential of BioCCS to sequester carbon?

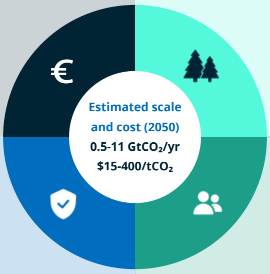
### Economic performance

**CapEx**
Lower costs for retrofitted plants.
**OpEx**
High costs to process $CO_2$ and transport to storage site. Costs are lower for highly concentrated $CO_2$ streams within BioCCS plants.

### Environmental performance

Land-use change, biosphere integrity, freshwater impacts and nutrient flows are impacted less by non-dedicated energy crops or by utilising biomass side-streams (agricultural/forestry residues).

Water and land requirements are higher for plantation-based BioCCS.



Estimated scale and cost (2050)
0.5-11 $GtCO_2$/yr
\$15-400/$tCO_2$

### Resource security

Lower energy constraints if the energy produced in biomass conversion can be utilised.

Additional dedicated energy crops for biomass production require new land conversion and water for irrigation.

### Social and governance performance

Potential need for international biomass transport and impact on food systems due to additional land area requirements.

Unfavourably perceived by stakeholders.

# Current unknowns and future research perspectives

The future availability of non-plantation based feedstock is uncertain, and the limited amount will need to be shared amongst other potential feedstock uses (e.g. construction materials, biochar or alternative fuel production). Climate change may impact biomass growth rates and constrain future feedstock quantity.

There is uncertainty in the CDR potential and BioCCS cost due to the lack of a standardised methodology. Clarity is needed on feedstock value chain carbon accounting as uncertainty exists as to whether many BioCCS projects actually create net-negative emissions.

Carbon storage availability is currently low and the benefits/risks of on/offshore storage are still being studied.

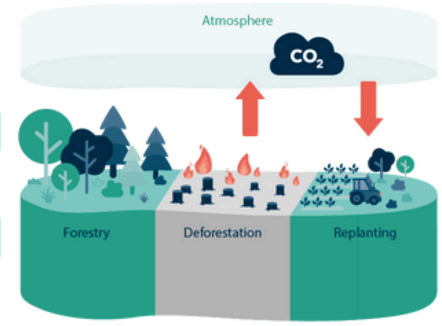
## RECOMMENDATIONS

- Ensure that certification schemes provide appropriate incentives to securely capture of all concentrated $CO_2$ streams regardless of carbon emission type (fossil, biogenic); account for the carbon throughout the entire value chain to enable a systemic assessment of each BioCCS project and determine the net removal of carbon.
- Conduct system-level BioCCS project life-cycle impact assessments to determine impacts on land-use change, natural resources, ecosystem health, biodiversity, nutrient flows and soil carbon stocks, measured against potential trade-offs with planetary boundaries and the achievement of Sustainable Development Goals.
- Develop policies that support a transition towards plant-based diets e.g. EAT-Lancet planetary health diet that repurposes pastureland and alleviates land resource demand.
- Prioritise sustainable feedstock sources such as municipal waste, forestry and agricultural residues, and pulp and paper mills to avoid further transgression of planetary boundaries. Prohibit high quality and high value biomass as a feedstock in bioenergy.
- Source feedstock biomass sustainably, in full compliance with EU and international regulations; ensure that biodiverse ecosystems are not converted into biomass plantations. Use limited biomass sources in hard-to-abate sectors where no other appropriate feedstocks are available.
- Foster international trade and cooperation to address uneven distribution of domestic capacities such as biomass resources and storage sites.

# Afforestation and Reforestation

A practice which enhances natural carbon stores and can reduce emissions

Biogenic storage (soils, vegetation) | Land-based biological capture



| | |
|---|---|
| **Expected permanence** | decades-centuries |
| **Reversal risk** | high |
| **Uncertainty in amount of initially captured carbon** | medium |
| **Uncertainty in amount of carbon stored over time** | high |
| **Ease of MRV** | low |
| **Key co-benefits** | Can enhance biodiversity, ecosystem function |

## What are afforestation and reforestation and how do they store carbon?

Afforestation (A) involves planting new trees and increasing forest cover in previously non- forested lands, whereas reforestation (R) refers to replanting trees on recently deforested or degraded land. Forests act as carbon sinks as they remove $CO_2$ from the atmosphere via photosynthesis and store it in living biomass, dead organic matter, and forest soils. Carbon can accumulate in the stem and branches (above-ground biomass) but also in the roots (below-ground biomass) and soil. Continuous management of forest biomass is necessary to retain carbon in the vegetation and soils, hence this storage type is vulnerable to leakage and therefore likely to be temporary. Afforestation and reforestation practices that prioritise native mixed species, instead of non-native monoculture plantations, provide extra ecosystem functions and boost biodiversity.

Current annual rates of carbon storage from land-based sequestration (includes afforestation, reforestation and existing forest management) are estimated at 2 Gt $CO_2$ according to the State of CDR report from 2023.

Relevant regulatory frameworks: Land Use, Land-Use Change and Forestry regulation, Nature Restoration Law, proposal for a Monitoring Framework for Resilient European Forests. Society has agreed to several biodiversity and ecosystem restoration targets as set out in the Kunming-Montreal Global Biodiversity Framework and the Bonn Challenge.

## Advantages

### MULTIPLE CO-BENEFITS

Reforestation has extensive co-benefits. It contributes to nature restoration, soil health, biodiversity, biosphere integrity and climate stabilisation.

### € LOW COST

A/R already occurs and is cheaper to implement than other NETPs. Little additional infrastructure is required.

### POSITIVE PUBLIC PERCEPTION

Generally A/R is well-perceived by the public.

### ECONOMIC BENEFITS

Projects can empower and provide economic benefits to local communities.

## Challenges

### HIGH LEAKAGE RISK

Carbon stored in forest vegetation is vulnerable to disturbances such as wildfires, pests and disease, as well as land ownership change, where forests may be lost.

### HARD TO QUANTIFY STORED CARBON

Carbon stored below ground carbon is hard to measure. Geographical location affects forest capacity to sequester carbon and bears associated climate feedbacks (e.g. albedo, evapotranspiration).

### LIMITS ON STORAGE CAPACITY

Sequestration rate and forest growth is slow. Eventually, forests saturate, and therefore release as much $CO_2$ (e.g. from trees dying) as they absorb.

### LOCAL COMMUNITY RIGHTS

Projects may not always prioritise the rights of local and marginalised communities, which are often excluded from decision-making processes.

### ADDITIONAL LAND REQUIRED

Afforestation on previously non-forested land can lead to extensive land-use change, exacerbating food insecurity, land conflict, and adding pressure onto planetary boundaries.

### ADVERSE ENVIRONMENTAL IMPACTS

Afforestation projects on previously non-forested land can demand significant fertilisation and irrigation inputs. Projects can also involve the introduction of non-native species.

# What is the sustainable potential of afforestation and reforestation to sequester carbon?

## Economic performance

**CapEx**
Costs for roads and irrigation systems vary depending on the scale and location of the project. Potential increases in land prices will drive up costs.

**OpEx**
Sustained but low costs for continuous forest and land management.

## Environmental performance

Depends on vegetation type and species diversity, fertiliser use and irrigation needs. Potential for beneficial land-use change, improved biosphere integrity, freshwater impacts and nutrient flows under reforestation using diverse and native species. Afforestation with plantations may lead to loss of biodiversity.

**Estimated scale and cost (2050)**

**0.5-10 $GtCO_2$/yr**

**\$0-240/$tCO_2$**

## Resource security

Substantial additional land area will be required for afforestation projects.

Reforestation will also require land conversion, given that the majority of agricultural areas were established on previously forested land.

## Social and governance performance

A/R carries popular public support due to expected positive consequences for nature and future generations.

Risk of reversal is strongly linked to land use and management policies.

# Current unknowns and future research perspectives

It is not clear to what extent A/R is compatible with other land-based NETPs, considering economic, political, and social pressures on land area for food and urban development.

Climate feedbacks from the emissions of non-$CO_2$ greenhouse gases, volatile organic compounds, evapotranspiration and albedo changes can counterbalance the climate mitigation from the reduction in atmospheric $CO_2$ concentrations. These impacts need more accurate quantification to clarify the net climate benefit.

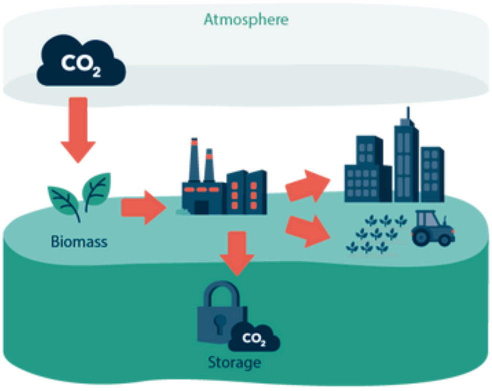
It is unclear what the continued impact of climate change will have on the ability for forests to grow, survive and store carbon, further complicating accounting, MRV and overall CDR efficiency.

## RECOMMENDATIONS

- Align climate and nature restoration regulation to achieve better, more coherent environment policy.
- End deforestation, protect old forests, ban illegal and intensive logging, reduce commercial plantations, and avoid harvests for short-term uses (such as for bioenergy, pulp and paper); ensure that the amount of harvested biomass does not exceed the capacity for forests to grow biomass to replace the losses.
- Adopt close-to-nature forestry management and other sustainable practices including planting mixed, native species and promoting old-forest growth; continue forest management after saturation to prevent disturbances from releasing sequestered carbon.
- Implement a large-scale food system transformation, in line with the EAT-Lancet planetary health diet to free up land, contribute to forest restoration, and to avoid conflicts with food production and security; prioritise reforesting and restoring degraded and desertified lands in primary and secondary forests.
- Take into account trade-offs (biosphere integrity, land use change, ecosystems, water cycle), local conditions, climate conditions, and climate feedbacks (surface albedo or evapotranspiration processes) in A/R projects.
- Adopt a rights-based approach that respects land rights of local and indigenous communities

# Biochar

A material that stores carbon and can reduce $CO_2$ emissions



| | |
|---|---|
| **Expected permanence** | decades to millennia |
| **Reversal risk** | medium |
| **Uncertainty in amount of initially captured carbon** | low |
| **Uncertainty in amount of carbon stored over time** | high |
| **Ease of MRV** | medium |
| **Key co-benefits** | increased crop yields, reduced soil N2O emissions, soil pH, reduce use of synthetic fertiliser |

## What is biochar and how does it store carbon?

Biochar is produced through the thermal decomposition of biomass in the absence of oxygen, in a process called pyrolysis, at a feasible temperature range between 450°-600°C. Heating levels above this range can create liquid form 'bio-oil' and 'pyrogas'.

Biomass can be obtained from a variety of sources, such as urban and municipal waste or agricultural, plant and forestry residues as well as dedicated biomass crops, and its quality determined by its feedstock source and the temperature at which it was produced. For example, a woody feedstock that was heated beyond 450°C has greater stability and a lower decay rate than manure-derived feedstock, heated at a lower temperature.

Permanence and reversibility are dependent on labile and recalcitrant carbon fractions, storage, and storage medium. Biochar can be added to construction material, such as cements and tar, or can be added to soils as it enriches the natural soil carbon sink. Research has shown that the recalcitrant portion of biochar is highly stable, however, due to a lack of long-term field studies, the potential release of stored carbon in biochar over time periods relevant for CDR is unclear.

According to the latest European Biochar Industry report, by the end of 2023, biochar production reached around 49 000 t (equivalent to over 130 000 t $CO_2$e).

Relevant regulatory frameworks: Renewable Energy Directive; Land Use, Land-Use Change and Forestry Regulation; Regulation for the purpose of adding pyrolysis and gasification materials as a component material category in EU fertilising products as a fertiliser.

## Advantages

### MULTIPLE CO-BENEFITS

Physical properties of biochar (e.g. high porosity) provide a range of co-benefits for agriculture, such as increased soil nutrient and moisture retention.

### MIXED FEEDSTOCK

No separation of feedstock types is required throughout the pyrolysis process.

### SMALL-SCALE DEPLOYMENT

Can be widely and rapidly deployed through multiple small-scale plants, utilising locally sourced and sustainable biomass side- streams.

### COST-EFFICIENT

Economic viability is high; co-produced syngas and bio-oil can be sold for profit, generating revenue to the plant operators.

## Challenges

### STANDARDISED CERTIFICATION CHALLENGING

The numerous storage options for biochar makes a standardised approach to certification of permanently stored carbon with certainty challenging.

### LESS CDR EFFICIENT

Lower CDR efficiency than other negative emission technologies and practices due to carbon lost during pyrolysis process and decay.

### LIMITS ON STORAGE CAPACITY

Overall biomass demand will increase, leading to competition with other biomass-based NETS such as BioCCS.

### HARD TO MONITOR

Permanence of carbon storage biochar and reactivity in open field applications is still unproven. When applied over a large area, monitoring the dispersed storage of extracted $CO_2$ and adhering to MRV requirements with certainty is challenging.

### ECOSYSTEM DEPENDENT CO-BENEFITS

Agricultural benefits are dependent on the soil, biochar properties, climate conditions and the interaction between these.

### POTENTIAL CLIMATE FEEDBACKS

Albedo changes may result, depending on the application method and the land on which biochar is applied.

## What is the sustainable potential of biochar to sequester carbon?

### Economic performance

Cheaper than other NETPs.

**CapEx**
Cost of leasing land, materials, machinery and trucks, feedstock and energy.

**OpEx**
Labour (farmer or pyrolysis operator), maintenance, and utilities.

### Environmental performance

Biosphere integrity and land-use change where wood or purpose grown crops are used as feedstocks.

Intensive freshwater use when biomass pyrolysis is based on feedstock from irrigated plantations.

**Estimated scale and cost (2050)**
**0.3- 6.6 $GtCO_2$/yr**
**\$10-345/$tCO_2$**

### Resource security

Dedicated crops and large-scale biomass plantations place pressure on land, and own crops and large-scale biomass consequently, on food security.

Risk of water scarcity for other uses e.g. food production.

May produce energy and useful products (pyrogas, bio-oil).

### Social and governance performance

More resilient soils will secure livelihoods.

Allows for local, bottom-up infrastructure, and is therefore less dependent on biomass prices.

## Current unknowns and future research perspectives

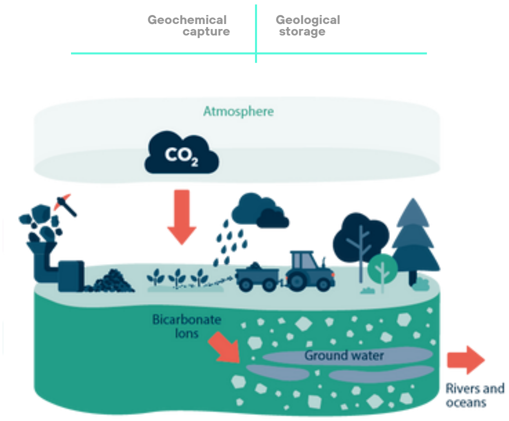
Reactivity of biochar in different storage mediums (e.g. soils, buildings materials, concrete, asphalt, tar) and the proportion of labile (chemically unstable) and recalcitrant (stable) biochar carbon retained in storage medium e.g. soils over long time periods.

Interaction between biochar and soil properties at the application site and the influence on total carbon loss (i.e. from soil organic carbon stocks and biochar degradation) and on ecosystem co-benefits of biochar application in different soil types e.g. water-holding capacity, crops, yield, climate conditions, non-$CO_2$ GHG emissions, and binding of heavy-metal pollutants.

## RECOMMENDATIONS

- ★ Design long-term duration field experiments to provide an increased understanding on biochar properties, functions, and to help develop a comprehensive biochar application policy.
- ★ Ensure that the addition of biochar to soil suits the application context by, amongst others, considering climate and soil conditions. Create a regulation with a robust methodology that monitors dispersed storage, potential albedo change, accounts for decay rates and emissions, and assigns liability for reversal.
- ★ Ensure that biomass is sourced from side streams such as agricultural and forestry residues, or food waste to avoid accumulating a carbon debt, taking land away from nature, competition with other NETPs, or food insecurity.
- ★ Avoid growing dedicated crops. Prioritise growth in abandoned cropland or apply a land- and calorie-neutral pyrolysis system that requires fewer fertilisers, pesticides and irrigation, while providing co-benefits.

# Terrestrial enhanced weathering



A practice that enhances a natural process to remove $CO_2$

| | |
|---|---|
| Expected permanence | millennia |
| Reversal risk | low |
| Uncertainty in amount of initially captured carbon | high |
| Uncertainty in amount of carbon stored over time | high |
| Ease of MRV | low |
| Key co-benefits | potential increased crop yields, reduced fertiliser use |

## What is terrestrial enhanced weathering and how does it store carbon?

Terrestrial enhanced weathering (TEW) is the application of silicate or carbonate mineral particles with high reactive surface area to soils. These minerals dissolve in water and react with $CO_2$ to produce bicarbonate ions that flow via groundwater to rivers and to the ocean, or mineralise on land, becoming stable carbonates. This does mean that the time of carbon removal is not identical to the time of application. Both the dissolved ions and the formed minerals are highly stable storage mediums that lock carbon securely for long periods of time (>10 000 years), with a low risk of leakage.

Different minerals can be used in enhanced weathering which have different chemical composition, dissolution reactions, $CO_2$ sequestration capacity, and contain different toxic heavy metals or compounds that could be health or environmental risks. Two commonly applied minerals are basalt and dunite. Basalt requires substantial mining operations and material transport, which if using fossil resources, will offset the climate benefits of the carbon removal itself. Dunite-based TEW requires less material than basalt but does have higher toxicity due to substantial nickel content in the mineral. Hence each project requires assessment of its unique impacts, based on, for instance, application location and mineral applied.

Lime is commonly applied in agricultural practice to control the pH level in soil, pH but its use in carbon removal and storage is novel and research is on-going. Its usage as a NETP is not commonly considered in country portfolios within the EU. According to the IPCC, economic, environmental and technological feasibility is first expected after 2030 or even 2050.

Relevant regulatory framework: There is currently no specific EU legislation that regulates enhanced weathering.

## Advantages

### PERMANENT STORAGE

Sequested carbon is stored permanently with low risk of stored carbon being re-emitted.

### NO ADDITIONAL LAND REQUIRED

Existing agricultural land can be used for TEW and its application may enhance crop yields and reduce fertiliser use.

### SIMILAR TO SOIL PH MANAGEMENT

Enhanced weathering is a similar process to lime application to soils and standard tests exist that can be used to measure reaction rates in soils for relevant projects.

### COST-EFFICIENT

Comparatively cost-effective application, with large theoretical and indefinitely sustained capacity.

## Challenges

### HIGH VALUE CHAIN GHG EMISSIONS

Both the rock crushing process and associated mining of minerals have high upfront GHG emissions.

### DIFFICULT TO QUANTIFY IN FIELD

$CO_2$ sequestration is not immediate after application. The slow reaction rates are difficult to quantify accurately in the field.

### HARD TO MONITOR

Applied over a large area, monitoring the dispersed storage of extracted $CO_2$ and adhering to MRV requirements with certainty is difficult.

### SEQUESTRATION RATES VARY WITH LOCATION

Rate of $CO_2$ sequestration is variable due to different soil chemistry. In certain locations $CO_2$ may be released and lower the CDR efficiency.

## What is the sustainable potential of terrestrial enhanced weathering to sequester carbon?

### Economic performance

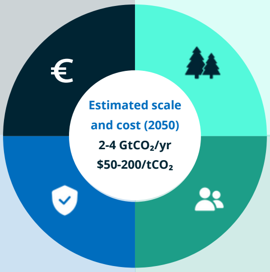
**CapEx**
High initial investment in mining/grinding/ transport infrastructure.

**OpEx**
Sustained monitoring, maintenance costs. High costs to power rock crushing, transport of minerals to deployment site. Application costs comparatively low.

### Environmental performance

Large amounts of minerals required and sustainable sourcing is unlikely. Environmental impacts of mining depend on the source mineral. Mining can also cause freshwater pollution and GHG emissions.

Mineral application can leach metals into soils/groundwater.



Estimated scale and cost (2050)
2-4 $GtCO_2$/yr
\$50-200/$tCO_2$

### Resource security

No extra land area is required for application, but maximum mineral application thresholds will exist.

Crushing, grinding and transportation of rock material could strain available renewable energy sources and transport networks.

### Social and governance performance

Environmental impacts of mining, risk of human rights abuse in mining operations, international material transport. Mining impacts on human health (e.g. carcinogen production, fine particle pollution), but these may be outweighed by climate mitigation health benefits.

## Current unknowns and future research perspectives

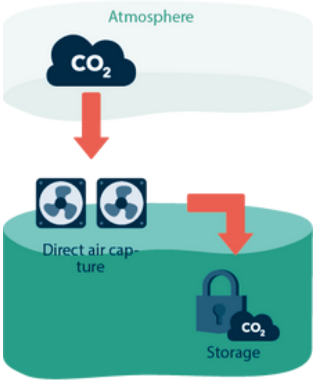
Field studies have not yet been able to replicate theoretically possible dissolution rates. Mineral reactivity is strongly influenced by environmental conditions, working more favourably in warm and humid locations (e.g. Brazil, SE Asia, China, India). More accurate modelling alongside field measurements is therefore necessary to boost understanding of chemical reactions, the dispersion of the mineral, reaction rates and any potential loss that may occur from secondary mineral precipitation.

The rate of grain dissolution is a key factor for the carbon sequestration rate within the weathering process. However, more research is needed to measure how fast rock grains dissolve under different soil conditions in the field, and to optimise its application. New methods for enhanced rock weathering are being developed, including the use of catalysts or organisms such as lichen or mosses, which, when applied to rocks, can dissolve them by modifying rock surface chemistry.

## RECOMMENDATIONS

- Develop appropriate and comprehensive MRV for the carbon sequestered and stored, as well as standardised environmental impact assessments to support TEW applications as permanent CDR. This may include standardised modelling methodologies that enable accurate MRV of dispersed carbon stores and are validated by measurements of mineral dissolution rates in the field weathering rates for different minerals.
- Consider interim incentives based on the co-benefits of enhanced weathering, and vehicle comprehensive MRV as CDR is being developed.
- Align the scale of enhanced weathering deployment with the scale of sustainable mineral powder availability, as opposed to the potentially inexhaustible application to agricultural fields.
- Apply sustainability assessments and standards to mineral sources both inside and outside the EU and ensure all potential GHG emissions and environmental impacts are accounted for. Adapt existing EU environmental protection legislation, where needed.
- Ensure project permits consider suitable locations for mineral extraction and grinding that have ample renewable energy available and are close to application sites so as to minimise value chain GHG emission.

Permanent geological storage | Chemical capture



# DACCS

A process that removes $CO_2$ directly from the atmosphere

| | |
|---|---|
| **Expected permanence** | millennia |
| **Reversal risk** | low |
| **Uncertainty in amount of initially captured carbon** | low |
| **Uncertainty in amount of carbon stored over time** | low |
| **Ease of MRV** | high |
| **Key co-benefits** | non |

## What is DACCS and how does it store carbon?

Direct air capture with carbon storage (DACCS) refers to the chemical extraction of $CO_2$ from the atmosphere by chemical adsorption, followed by the recovery and compression of $CO_2$ into a concentrated liquid, and storage in geological reservoirs. It is an example of removals with easy MRV because the capture and storage processes are relatively easy to quantify and measure. The process to separate $CO_2$ from the other components of ambient air is either done through absorption or adsorption. Once extracted, the carbon is then stored in geological reservoirs such as saline aquifers, or in other mineral forms in the Earth's crust.

Solid sorbent and liquid solvent DACCS are two common approaches used to capture $CO_2$ directly from the air. In the liquid solvent DACCS process, high-grade heat (900°C) is supplied by natural gas or hydrogen, with electricity sourced from the power grid. $CO_2$ emissions resulting from natural gas combustion are assumed to be captured within the plant limits. In the solid sorbent DACCS process, heat and electricity are both obtained from the power grid, using an industrial heat pump which converts electricity to low-grade heat (100°C). Newer capture technologies use more economical, reversible carbonate-based chemical reactions (carbonation and calcination), which are cheaper.

As of February 2024, there are over 20 DAC/DACCS initiatives in Europe. Current capacity at one of the largest plants in operation, Mammoth, is on the scale of 36,000 tons of $CO_2$ each year.

Relevant regulatory framework: Geological storage is currently regulated under the EU CCS Directive. According to the IEA, potential cross-boundary $CO_2$ transport may be regulated under the London Protocol, once ratified.

## Advantages

### PERMANENT STORAGE

Sequested carbon is stored permanently with low risk of reversal.

### Technology Readiness Level

DACCS is one of the more developed technologies (TRL 6). It is already being piloted.

### MRV

Easy to quantify how much carbon is removed and stored. Baseline definition is straightforward and DACCS is, by default, considered additional.

### ENVIRONMENTAL BENEFITS

Low impacts on terrestrial biosphere, generally not constrained by biophysical limitations and may provide valuable freshwater source in arid regions.

## Challenges

### ENERGY INTENSIVE

Dependent on plentiful (and renewable) energy and heat source. Approximately 200mk$_2$ of non-arable land is needed for renewable energy generation to remove 1 Gt of $CO_2$.

### PLANT LOCATION

Limitations on plant location due to necessary proximity to renewable energy supply. Storage capacity limited due to low current capacity of stable and permanent storage reservoirs.

### FEW CO-BENEFITS

DACCS has fewer associated co-benefits compared to land-based sequestration or BioCCS.

### COST

Costs are high and infrastructure is expensive to build.

## What is the sustainable potential of DACCS to sequester carbon?

### Economic performance

**CapEx**
Relies on costly grid and electricity transmission expansion, $CO_2$ pipelines and storage facilities.
**OpEx**
High energy costs (heat, power) and high cost of $CO_2$ transport and storage.

### Environmental performance

Large amounts of minerals and metals are required for renewable energy infrastructure, which can impact water/air quality.

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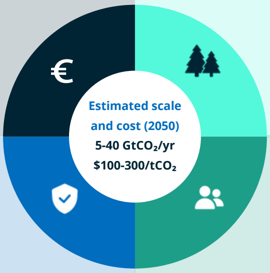


### Resource security

Requires substantial additional clean and renewable energy source.

Sustainability of sorbent materials depends on the material lifetime and $CO_2$ uptake efficiency.

### Social and governance performance

The type of energy source can incur human health impacts (water consumption, fine particle pollution).

Social barriers to large-scale DACCS include plant locations, risks to local energy security, as well as associated impacts of rare earth metal mining.

## Current unknowns and future research perspectives

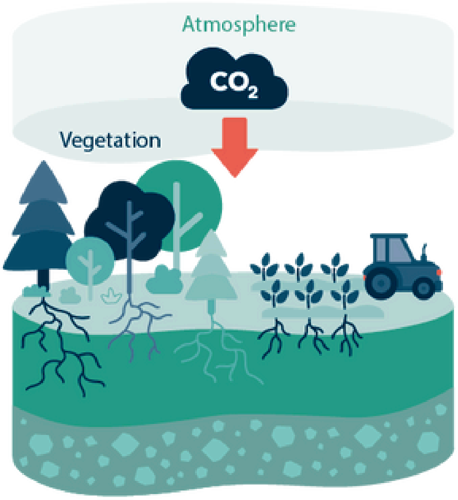
DACCS is currently expensive and its future cost is hard to predict. Experts believe that economies of scale, process optimisation, including the development of more efficient and less costly sorbents, will eventually decrease sorbent fabrication costs. Greater availability and subsequent lower cost of renewable energy could significantly reduce the energy costs of the technology. Options include novel configurations or technologies that use carbonation cycles rather than sorbent materials.

Regulation is currently limited to $CO_2$ storage in geological storage sites under the EU CCS Directive (2009/31/EC), which also sets out clear liability and monitoring mechanisms. However, clear international or European regulatory framework for the cross-boundary transport of carbon has not yet been developed.

## RECOMMENDATIONS

- Support renewable energy development to ensure DACCS-related energy requirements can be accommodated, as opposed to further straining energy demand on partially-renewable energy systems. This avoids harmful health impacts arising from non-renewable electricity generation.
- Acknowledge the uneven distribution of domestic capacity for renewable energy and permanent carbon storage for DACCS. Prioritise DACCS in regions where renewable energy is plentiful and ensure that the energy required for DACCS does not detract from grid decarbonisation. Ideally, locate DACCS plants in proximity to geological storage sites.
- Coordinate transboundary $CO_2$ transport and storage to achieve DACCS deployment at scale. Create legal instruments that include socio-political and ethical compensation or incentivisation mechanisms for Member States that are expected to host optimal DACCS. Respect sovereign rights to equity and development in transboundary initiatives with third countries.
- Ensure that policies coordinate key industries involved in capture, storage and transport of $CO_2$ and give certainty to stakeholders, incentivise financial investment and establish secure business models.

Land-based biological capture | Temporary biogenic storage



# Soil carbon sequestration

A practice which enhances a natural process to store $CO_2$ and can reduce emissions

| | |
|---|---|
| **Expected permanence** | decades |
| **Reversal risk** | high |
| **Uncertainty in amount of initially captured carbon** | medium |
| **Uncertainty in amount of carbon stored over time** | high |
| **Ease of MRV** | low |
| **Key co-benefits** | Enhances soil resilience, water retention and contri- bute to ecosystem integrity |

## What is soil carbon sequestration and how does it store carbon?

Soil organic carbon (SOC) sequestration occurs because plants capture atmospheric $CO_2$ via photosynthesis and convert it into organic carbon. Part of this organic carbon is then transported into soils, thereby increasing the soil organic carbon content. Sustainable management practices such as conservation tillage, cover cropping, plant/crop variety, organic amendments (compost or manure), and drastic reduction in synthetic fertilisers help to retain organic carbon in soils and maintain or restore soil health and stability.

Measures that enhance SOC are common practice within sustainable land management due to the resulting co-benefits that secure the livelihoods of farmers. Yet, as an activity-lead practice, stored carbon is not commonly quantified, and will likely vary depending on the particular ecosystem and geographical location conditions. Numerous habitats contain substantial amounts of organic carbon such as agricultural soils, forests, wetlands, and grasslands, but soil carbon content is unevenly distributed across Europe; northern countries tend to be carbon-rich whereas the Mediterranean region is carbon depleted. Despite a clear value to society, around two-thirds of EU soil ecosystems are in poor health, acting as an emissions source, as opposed to a sink. Continuous land management and consistent policy measures are necessary to support carbon retention in soils.

Relevant regulatory frameworks: Soil Monitoring Law (under negotiation), Common Agricultural Policy, Nature Restoration Law.

## Advantages

### IMPROVES SOIL HEALTH

Addressing SOC will improve soil quality and resilience and promote nutrient cycling in terrestrial ecosystems.

### ADDRESSES A HIGH EMISSION SECTOR

Adequate implementation of sustainable land management practices in agriculture could cut emissions in a top polluting sector.

### MULTIPLE CO-BENEFITS

Healthy soils fulfill societal needs such as food security, healthy ecosystems, and water storage.

## Challenges

### RISK OF STORAGE REVERSAL

SOC storage is vulnerable to disturbances that can re-emit stored carbon.

### ACCURATE QUANTIFICATION OF CARBON

Land management practices, soil types and climate conditions have different impacts on the soil carbon cycle. This complicates MRV and the design of methodologies.

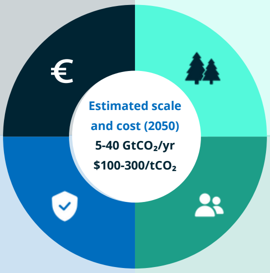
### LIMITED STORAGE CAPACITY

Biophysical constraints such as rainfall impact on vegetation growth rates, can reduce soil carbon sequestration capacity.

### CONTINOUS MANAGEMENT

Inadequate land management or transfer of land stewardship can transform soils into a carbon source, as opposed to a carbon sink.

# What is the sustainable potential of soil carbon sequestration?



Estimated scale and cost (2050)

$5\text{-}40\ \text{GtCO}_2/\text{yr}$

$\$100\text{-}300/\text{tCO}_2$

## Economic performance

**CapEx**

May be low unless purchase of equipment necessary e.g. for conservation tillage or composting/infrastructure changes, especially when no support system for land stewards exists.

**OpEx**

Sustained monitoring, maintenance costs as well as labour for land management practices.

## Environmental performance

Limitations on SOC storage capacity.

Impacts of climate change may increase storage vulnerability.

## Resource security

Not relevant, if implemented on existing agricultural or forestry land.

## Social and governance performance

Healthier soils boost food security, human health, and farmer livelihoods

High risk of contractual reversal. Success is highly dependent on agricultural policies and practices.

# Current unknowns and future research perspectives

SOC content impacts soil function and above a certain threshold ceases to additionally benefit the ecosystem. Further research is needed to establish these thresholds.

Influence of soil type, climate (e.g. change in rainfall patterns, rising sea levels, erosion) and management practices on SOC content. The realistic long-term capacity and potential of SOC sequestration long-term is not well understood.

## RECOMMENDATIONS

- Establish legally binding targets and sustainable management practices across all habitats that focus on protection, restoration and soil health, including its role in regulating water, air quality, assuring food production and supporting biodiversity. Focus policy on enhancing ecosystem integrity, while designating associated carbon sequestration as the co-benefit.
- Reform the Common Agricultural Policy to set higher targets, combining both activity and results-based goals, regenerative practices, and prevention of further degradation of soils and carbon stocks; apply tighter conditionalities that favour small scale farms, provide training, technical support, and advice to farmers.
- Shift dietary preferences towards a plant-based diet and adopt policies that seek to reduce food waste.
- Develop a standardised accounting, MRV and liability system, tailored to the different climate conditions and soil type, if the practice is incentivised by carbon removal units.
- Create detailed databases, including land use data, to measure and monitor soil systems and their health, including their baselines. Develop remote sensing and other machine learning techniques.

# Glossary

## Afforestation and reforestation

Both afforestation and reforestation describe the establishment of forests on land where, previously, there were no forests. The distinction between these two forestry activities is determined by how the land was used prior to the establishment of the forest. Afforestation refers to the "planting of new forests on lands that historically have not contained forests", according to the IPCC. Certain definitions provide more specific time periods, such as 50 years, whereas others refer to "historical time". Reforestation refers to the "planting of forests on lands that have previously contained forests but that have been converted to some other use". While afforestation generally presents a greater risk to the local ecology because of the human intervention involved, reforestation is generally intended to restore an area's natural ecosystem to the original state. See also the factsheet on "Reforestation and Afforestation".

## Albedo

"The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and the oceans have a low albedo. The Earth's planetary albedo changes mainly through varying cloudiness, snow, ice, leaf area and land cover changes." Some CDR approaches, such as afforestation and reforestation, may unintentionally alter the Earth's albedo. Intentional interventions to the Earth's albedo are generally classified as "Solar Radiation Management".

## Biochar

Biochar is a carbon-rich material and a form of charcoal. It is the product of biomass pyrolysis, which involves decomposing the biomass at high temperatures under low oxygen concentrations. Its complex chemical composition depends on the biomass used, the pyrolysis temperature and time, which is often tailored to its intended use. Biochar may be added to soils to improve soil function, to reduce GHG emissions from decaying biomass and soils, and for sequestration of the pyrogenic carbon in the biochar. A key issue with all biomass processes is the sustainable sourcing of that biomass given the potential environmental impacts (for example, harming biodiversity through deforestation or monoculture plantations), or social impacts (driving up food and/or land prices due to demand for land to grow biomass) that may result. Moreover, all biomass use implies demand for land that cannot be used for other means, as biomass and land are both finite resources. See also the factsheet on "Biochar".

## Biomass use and Bioenergy with carbon capture and storage (BioCCS and BECCS)

BECCS is a “negative emissions technology” where biomass is combusted to produce electricity, and the biogenic $CO_2$ is captured and transported to permanent storage sites. BioCCS is a broader term which refers to the use and conversion of biomass, followed by carbon capture and storage, and includes BECCS as well as other biomass use and conversion (e.g. fermentation or use of biomass for industrial processes). A key issue with these processes is the sustainable sourcing of biomass given the potential environmental (e.g. harming biodiversity through deforestation or monoculture plantations), or social impacts (e.g. driving up food and/or land prices due to demand for land to grow biomass). Moreover, all biomass use implies demand for land that cannot be used for other means, as biomass and land are both finite resources.

BioCCS can produce negative emissions when the carbon dioxide sequestered by sustainably growing biomass is converted and stored in permanent geological storage thereafter. However, the actual removal from the atmosphere only happens once the previously converted biomass has regrown (see also “Carbon debt”). In addition, the total emission balance of the process needs to be evaluated, and climate impacts due to biomass production, transport and processing need to be assessed. See definition of “Life cycle Assessment (LCA)” as well as the factsheet on “Biomass use with carbon capture and storage (BioCCS)”.

## Carbon credit

A carbon credit (see also “Carbon market mechanisms”) is usually measured (and verified) as 1 tonne of $CO_2$ equivalent which has been reduced or removed from the atmosphere. In this case, “equivalent” means GHGs are converted to the equivalent warming effect of $CO_2$ by multiplying the tonnes of emitted GHG by the associated global warming potential. Carbon credits are frequently used to offset or compensate for ongoing emissions on a tonne-for-tonne basis, a practice which is often associated with greenwashing, and which is questionable from a physical science perspective (see “Carbon market mechanisms”). Carbon credits must undergo measurement, reporting, verification, and have robust accounting procedures applied to avoid double counting. Investments that generate credits must demonstrate additional results beyond what would have occurred naturally (see “additionality” under “Accounting”). They should also have a low risk of reversal and avoid negative impacts on people and the environment.

## Carbon debt

In forestry, the carbon debt refers to the temporal displacement between $CO_2$ emissions when forest biomass is harvested (and is used for energy purposes, for instance) and the subsequent sequestration of carbon in new forest biomass. As such, it is the time lag between the harvesting of forests, and the replacement of the equivalent carbon that was released following the harvest through forest regrowth, which creates a “carbon debt”.

## Carbon dioxide removal

Carbon dioxide removal (CDR), also known as negative emissions or carbon removal, refers to physically extracting carbon dioxide already present in the atmosphere and permanently storing it underground, for example, in geological formations. The following criteria need to be met for an activity to qualify as a removal: (1) $CO_2$ is physically extracted from the atmosphere; (2) the extracted atmospheric $CO_2$ is permanently stored out of the atmosphere; (3) all GHG emissions associated with the removal and storage processes are comprehensively estimated and included; and, (4) more atmospheric $CO_2$ is permanently stored than GHGs are emitted in the removal and storage processes and their complete supply chains. CDR is only human-induced, and must therefore be distinguished from natural sequestration, which takes place, naturally, in forests, grasslands and wetlands, that act as “carbon sinks”. See also “Permanence”.

## Carbon farming

Carbon farming broadly refers to land management practices, particularly in agriculture and forestry, that enhance the amount of atmospheric $CO_2$ captured and sequestered in soils, vegetation and organic matter as organic carbon, or reduce land-based GHG emissions. It involves a range of activities, examples being the use of conservation tillage, catch and cover crops, sustainable use of fertilisers and pesticides, rewetting and conservation of wetlands, and agroforestry. Carbon farming should be done through a holistic approach, offering ecosystem services with the aim of increasing farm resilience, rather than optimising for the purpose of carbon sequestration at the expense of ecosystem health.

## Carbon management

Carbon management refers to the control and tracking of industrial carbon flows, with the aim of reducing net $CO_2$ emissions from large point sources. This is achieved using a range of technologies and practices that chemically capture $CO_2$ from flue gases, transport, use or store carbon. This is known as carbon capture and utilisation (CCU) and carbon capture and storage (CCS) respectively. CDR may result from these activities if the captured $CO_2$ is of atmospheric or biogenic origin, and the $CO_2$ is permanently stored. The term “carbon management” is, therefore, often used as a catch-all term for CCU, CCS and CDR, which risks obfuscating the crucial differences between each of these different activities, an example being, their distinct climate impacts. See also “Carbon capture and storage (CCS) and use (CCU)”.

## Carbon neutrality

Carbon neutrality, or net zero $CO_2$ emissions, refers to the “condition in which anthropogenic carbon dioxide ($CO_2$) emissions associated with a subject are balanced by anthropogenic $CO_2$ removals”. This means that the amount of $CO_2$ emitted to the atmosphere is the same as the amount of $CO_2$ removed from the atmosphere, and the atmospheric concentration of $CO_2$ is stable. Carbon neutrality will be achieved before climate neutrality because emissions of GHGs other than $CO_2$ will be much harder to eliminate and their removal more technically difficult, because of the lower atmospheric concentrations. See also “Net zero”.

## Climate neutrality

According to the IPCC, climate neutrality refers to the complete balance between residual GHG emissions and the amount of GHGs removed from the atmosphere. In simple terms: as many GHGs are added to the atmosphere as are taken back out, leading to a dynamic balance. The exact nature of this GHG balance is not yet clearly defined in policy, leaving ambiguity as to how residual non-$CO_2$ emissions will be counterbalanced. Under climate neutrality, the net impact of the climate, including local or regional human impacts on surface albedo or climate is also balanced. The EU has a 2050 climate neutrality target, embedded in the European Climate Law.

## Co-benefits

According to the IPCC, co-benefits are “(t)he positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors.” To illustrate, BioCCS may generate both a negative emission and a valuable product, such as district heating or electricity. Furthermore, when carefully implemented, certain land-based CDR approaches can bring about co-benefits for biodiversity, climate adaptation and food security. Concrete examples include improving soil health, reducing soil erosion and enhancing water retention. Given that many of these elements might actually be more important and valuable than the carbon stored itself (particularly considering the vulnerability of certain storage mediums), the use of the term “co-benefits” has been criticised for undermining other environmental objectives and promoting a narrow carbon-centric approach.

## Direct Air Carbon Capture and Storage

According to the IPCC, direct air carbon capture and storage refers to a “chemical process by which $CO_2$ is captured directly from the ambient air, with subsequent storage.” See also the factsheet on “Direct Air Carbon Capture and Storage (DACCS) ”.

## Enhanced Weathering

According the IPCC, enhanced weathering entails “enhancing the removal of carbon dioxide from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans”. See also the factsheet on “Enhanced Weathering”.

## False equivalence

A false equivalence or false fungibility between removals and emissions reductions is established when it is erroneously assumed that a tonne of $CO_2$ removed from the atmosphere is equivalent or fungible to a tonne of $CO_2$ not emitted. This may also occur when considering the impact of one tonne of removals via different CDR approaches with varying characteristics. See also “The carbon cycle” and “Separate activities”.

## Feedstock

Feedstock refers to the raw material used in various processes. Feedstock may be biogenic, such as forestry and agriculture residues, or non-biogenic, such as fossil fuels. In a BioCCS plant, for instance, the biogenic feedstock is combusted to extract the previously sequestered $CO_2$ which is then captured and permanently stored. The use of sustainable feedstock is essential to minimise environmental impacts.

## False Fungibility

See "False equivalence".

## Geoengineering

The Convention on Biological Diversity has defined climate-related geoengineering as a "deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts". Common techniques include (1) GHG removal, also known as "negative emission techniques" (some of which classify as forms of CDR), and (2) sunlight reflection methods, also known as "Solar Radiation Management" or Albedo management". The definition excludes carbon capture at source from fossil fuels but recognises that the carbon storage components of that process can be shared with geoengineering techniques.

## Greenhouse gas

Greenhouse gases (GHG) absorb wavelengths of radiation emitted by the Earth's surface, the atmosphere and by clouds. This absorption traps heat in the atmosphere and contributes to warming of the Earth's surface, also known as the greenhouse effect. There are many natural GHGs e.g. water vapour ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$) and ozone ($O_3$), in addition to human-made ones e.g. halocarbons and chlorine- and bromine-containing substances.

## Hard-to-abate

See "Residual emissions".

## Industrial carbon removals

Industrial carbon removals differ from approaches with non-permanent sequestration in biological stores such as in afforestation, reforestation, or soil carbon sequestration. Industrial carbon removals rely on carbon capture and storage (CCS) technology to capture $CO_2$ directly from the atmosphere, as with DACCS, or to capture biogenic $CO_2$ from power plants or industrial processes, as with BioCCS. To be considered an effective removal, the captured carbon must be stored permanently and align with the four principles of carbon dioxide removals. These approaches frequently entail high costs and energy requirements (e.g. DACCS) or strong needs for natural resources (e.g. BioCCS), thereby raising sustainability concerns.

## Land-based sequestration

For the purposes of this handbook, land-based sequestration refers to the biogenic absorption of $CO_2$ - through a process known as photosynthesis - and consequent storage within the plant or soil. Examples of land-based sequestration are soil carbon sequestration, afforestation and reforestation.

## Land use and land use change

Land use (LU) refers to human action (including the total of arrangements, activities and inputs) undertaken in a certain land cover type. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g. growing crops, livestock grazing, timber extraction, conservation, and city dwelling). Land-use change (LUC) involves a change from one land use category to another or the conversion of land from one purpose to another by human intervention. This change can involve transforming grasslands into croplands, for instance, or agricultural lands to forests.

Both land use and the change in land use can cause significant environmental impacts, affecting biodiversity, the global carbon cycle, the surface albedo, evapotranspiration, and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally, as described in the IPCC definition. LUC can also cause significant social impacts due to displacement of indigenous or local populations, or of economic or cultural activities they rely on. It therefore has significant human rights implications. Indirect land-use change (ILUC) refers to market-mediated or policy-driven shifts in land use that cannot be directly attributed to land-use management decisions of individuals or groups. For example, if agricultural land is diverted to biofuel production, forest clearance may occur elsewhere to replace the former agricultural production. ILUC can be hard to trace or quantify due to it potentially occurring in far-flung geographic regions, and because of complex interactions with global trade flows and economic activities.

## Leakage

Leakage refers to the changes in emissions along the value chain that lead to the emission, or remission, of carbon – it is therefore also commonly referred to as “carbon leakage” or “emissions leakage”. Carbon flows that “leak” can be substantial and predictable. Physical leakage refers to the leakage of stored $CO_2$ from geological storage sites or during transport. GHG emissions from value chain activities such as transport or land-use change are also considered as leakage. It can also occur when a country or sector implements mitigation measures that shift emissions, direct or indirect, to a different country or sector.

## Land-based sequestration

The IPCC has defined life cycle assessments as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its life cycle. Significant emissions, both within upstream (e.g. biomass origin and energy use) and downstream (e.g. transport emissions and co-product fate) steps associated with the removal process must be accounted for. This includes scope 1, 2, 3 emissions. Such a robust LCA assessment, involving a so-called “cradle-to-grave" system, is required to confirm that the removal technology led to an overall decrease in atmospheric GHG concentrations and thereby achieved negative emissions. See also “Accounting”.

## Mitigation deterrence

Mitigation deterrence occurs when carbon removals (or the perception that they will become available in the future) undermine or detract from current and future efforts to reduce emissions in the first place. Mitigation deterrence has already had an impact on climate policy, for instance by using removals to facilitate the continued exploitation and consumption of fossil fuels and generating long-term climate targets which already assume large, possibly unrealistic, volumes of CDR.

## Negative Emissions Technologies and Practices (NETPs)

NETPs refer to technologies and practices which can be used to create so-called negative emissions or carbon dioxide removal. This can include technologies such as DACCS or practices that enhance soil carbon sequestration.

## Net zero

Net zero emissions is the state achieved when anthropogenic emissions of GHGs to the atmosphere are balanced by anthropogenic removals over a specified period. This is also referred to as “Carbon neutrality” or “Climate neutrality”. This involves a combination of deep emission reductions and technologies that physically remove GHGs from the atmosphere and permanently store it.

## Pathways

Pathways consist in the temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals, for instance, limiting global warming to 1.5°C. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales.

## Residual emissions

Currently the concept of residual emissions is neither consistently defined or used. In this handbook, we define residual or hard-to-abate emissions as those emitting activities that society deems necessary and cannot or will not abate. As such, $CO_2$ must be permanently removed to enable the activity to persist. Some stakeholders use a definition closely related to the marginal cost of abatement: the most expensive emissions to reduce are deemed “residual”. However, this minimises societal and political agency. A cost-focused definition could be used to define GHGs and radiative forcing impacts of private jets as “residual” emissions, even if they are relatively easy to abate at a policy level.

The definition of what classifies as residual is likely to change depending on technological availability, societal necessity or economic conditions at any point in time. In any case, residual emissions must be narrowly defined to avoid using limited removals as a counterbalance for emissions which could otherwise have been abated.

## Reversal

A reversal occurs when the absorbed, sequestered, or stored carbon in a sink is re-released into the atmosphere. The variable risks of reversal of different carbon stocks must be taken into account, for example, forests may suffer from unforeseen anthropogenic (e.g. illegal logging), non-anthropogenic (e.g. disease and disaster), or climate change-induced (e.g. warming) reversal risks. Reversal risks can be extremely challenging to predict or quantify as they can happen rapidly or over centuries. As such, schemes or standards that only require monitoring and management of potential reversal on annual to decadal timescales may undermine efforts to achieve and maintain net zero. Moreover, strategies to compensate for the non-geophysical permanence of a given sink require strong governance and may involve significant costs, potentially making them costlier than stores with a lower risk of reversal. See also “Permanence”.

## Sink

A reservoir (natural or human, in soil, ocean, geological, and biological) where a GHG, an aerosol or a precursor of a GHG is stored.

## Soil carbon sequestration

Soil carbon sequestration refers to land management practices that enhance the soil organic carbon content, thereby drawing down $CO_2$ from the atmosphere or retaining it for longer than it otherwise would. See also factsheet on "Soil Carbon Sequestration".

## Solar Radiation Management

Intentional interventions to the Earth's albedo are generally classified as 'solar radiation management'. These interventions are outside the scope of this handbook, even if CDR may unintentionally modify albedo.

## Sustainability

Sustainability, as defined by the IPCC is "a dynamic process that guarantees the persistence of natural and human systems in an equitable manner". For CDR, a comprehensive definition of sustainable use of natural, physical and financial resources will be needed to ensure the long-term and sustained deployment of these technologies and practices within safe and governable boundaries. This implies that attention is not only given to "carbon" or "climate" issues, but also to wider environmental, social and economic issues, such as biodiversity, climate adaptation and human rights.

## Technology readiness level

According to NASA, "Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the project's progress. There are nine technology readiness levels. TRL 1 is the lowest ("basic principles observed and reported") and TRL 9 is the highest (system is successfully proven to work)".

## Trade-offs

A trade-off exists where an improvement of one aspect of the environment leads to the sacrificing of a different aspect. The IPCC has defined trade-offs as “a competition between different objectives within a decision situation, where pursuing one objective will diminish achievement of other objective(s)”. It could occur when, due to adverse side effects, a policy or measure aimed at lowering GHG emissions reduces outcomes for biodiversity conservation, thereby potentially reducing the net benefit to society or the environment. Or, where a DACCS plant, which is highly efficient at removing carbon, exacerbates pressure on renewable energy and water demand. Trade-offs must be distinguished from synergies, which represent scenarios where enhancing one desirable outcome leads to the enhancement of another.

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# NEGEM PROJECT

The NEGEM project – Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways – is a Research and Innovation Action funded by the EU Horizon 2020 Programme (Grant Agreement No. 869192) that aims to assess the realistic potential of NETPs and their contribution to climate neutrality, as a supplementary strategy to reducing emissions.

Its assessment goes beyond the perspectives of climate physics and economics, which currently provide the basis for climate scenario modelling. It applies a multi-disciplinary approach based on crosscutting and integrated analyses of technical, environmental, social, and economic aspects, to provide an informed assessment of the impact, acceptability and feasibility of NETPs deployment potentials within planetary boundaries. Ultimately, NEGEM aspires to outline concrete deployment pathways and draw a long-term vision supporting EU efforts for the Paris Agreement.

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