NEGEM

**Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways**

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# Executive Summary

The Paris Agreement, signed in 2015, establishes 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 more commonly known as 'net zero GHG emissions'.[1] To reach net zero targets, substantial emissions reductions of over 95% across all sectors 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 play a crucial role in counterbalancing residual emissions.[2] It could be carried out through emerging negative emissions technologies and practices (NETPs) that enhance natural processes or use novel approaches, and span a range of technological readiness, potential physical limitations, resource dependencies, adverse impacts, and co-benefits. Given the trade-offs, challenges for storage, permanence and liability for reversals, as well as the limits to upscaling removals, a diverse portfolio is needed; no one technology or practice can, alone, address the challenge of removing the required amount of $CO_2$ by 2050. Additionally, the risks that come with relying on one single approach, or a small subset of approaches, needs to be minimised.

This handbook summarises the key findings of the NEGEM project, a Research and Innovation Action funded by the EU Horizon 2020 Programme that attempts to assess the realistic potential of NETPs and their contribution towards climate neutrality, as a supplementary strategy to reducing emissions. The handbook discusses a list of concepts relevant to CDR, and explores six different NETPs: biochar, biomass with carbon capture and storage, direct air capture with carbon capture and storage, terrestrial enhanced weathering, reforestation and afforestation, and soil carbon sequestration. It is aimed at policymakers, NGOs, journalists, academics 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. The following key recommendations were found:

**OVERARCHING POLICY RECOMMENDATIONS**

1. Adopt a robust definition for carbon dioxide removal (CDR), 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 sequestration as supplements to emission reductions, as opposed to substitutes for decarbonisation, and favour contribution claim models. 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 carbon sequestration. To avoid conflation and maximise their contribution to tackling the climate crisis, address the differences between each activity. Disaggregate net zero goals by GHG emission type (highlighting their impact and atmospheric residence time) and removal/sequestration

[1] Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104, Article 4, https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[2] Allanah Paul et al., 'Who Should Use NETPS? Managing Expectations for NETP Demand: Considerations for Allocating Carbon Dioxide Removals', 2023, https://www.negemproject.eu/wp-content/uploads/2023/11/D6.5_Who-should-use-NETPS.pdf

category. Match the nature and timescale of emissions with corresponding removal approaches to accurately counterbalance these and devise effective pathways towards achieving net zero.

4. Implement robust accounting rules, certification methodologies, liability mechanisms and sustainability requirements for CDR based on careful consideration of implications and impacts to ensure real, sustainable removals.
   - Base monitoring, reporting and verification (MRV) on a solid quantification formula, always using the most conservative estimates and taking into account direct and indirect GHG emissions across the entire supply chain, both domestically and abroad, where applicable.
   - Prevent double-counting and double-claiming, also by applying corresponding adjustments 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 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.
5. Invest in research and development of CDR approaches and design policy mechanisms to allow for learning including data transparency obligations that enable cross-jurisdictional knowledge sharing. View failures as learning opportunities and as a means to hold constructive discussions on optimal deployment of CDR portfolios. To break down the barriers to sustainable deployment, devise alternate pathways focussed on emission reductions with limited to minimal reliance on CDR.
6. Adopt a holistic perspective on Earth system stability, with policies that integrate climate stabilisation and biosphere stewardship to account for their equally fundamental role in supporting Earth system resilience; integrate food system transformations, shifting society towards a plant-based diet that will free up land for nature restoration and production of biomass.
7. 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.
8. Adopt country-specific portfolios with realistic and responsible negative emission pathways for the EU, which consider the individual country's characteristics and apply a sustainable supply-driven approach, as opposed to one that is demand-based. Ensure effective allocation of constrained resources 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.
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.

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# Abbreviations

| | |
|---|---|
| **BECCS** | Biomass energy with Carbon Capture and Storage |
| **BioCCS** | Biomass use 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 "Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways" |
| **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 |

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# Introduction

**CDR in a nutshell**

Carbon dioxide removal (CDR) consists of physically extracting carbon dioxide already present in the atmosphere and permanently storing it away from the atmosphere, 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. Carbon dioxide can also be stored via natural processes such as in forests, wetlands, and grasslands that act as natural carbon sinks. Considering these are at high risk of human disturbances and require ongoing management, they are vulnerable to loss of stored carbon, and are therefore viewed as temporary forms of storage. However, the traditional divide between biogenic and technical removals is illusory, as technical solutions such as biomass with carbon capture and storage (BioCCS) and terrestrial enhanced weathering (TEW) also have a natural component to them. Nonetheless, where negative emissions occur through the biological carbon cycle, this creates additional benefits such as biodiversity protection and soil health.

Despite many existing uncertainties with removals, 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 GHG emissions is to be reached. According to the IPCC, the role of CDR is to:

1. 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.

Effectively, 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,[3] 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.

[3] Allanah Paul et al., 'Who Should Use NETPS? Managing Expectations for NETP Demand: Considerations for Allocating Carbon Dioxide Removals', 2023, https://www.negemproject.eu/wp-content/uploads/2023/11/D6.5_Who-should-use-NETPS.pdf

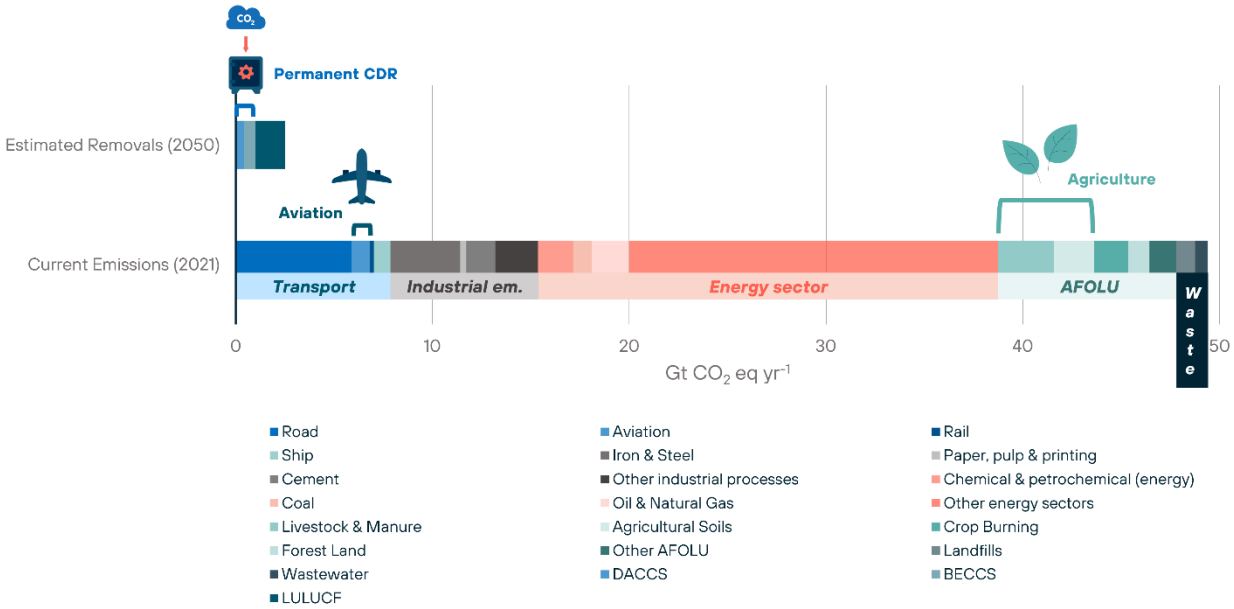



*Figure 1 Estimated carbon removals for 2050 compared to current emissions across several sectors. Source: NEGEM report "Who should use NETPs?"*[4]

Another important point is that of residual, hard to completely abate emissions. Given the likely limited capacity for CDR, its role should equally be limited to counterbalancing those last 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.[5] 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 GHG 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

[4] Allanah Paul et al., "Who Should Use NETPS"

[5] Jens Friis Lund et al., 'Net Zero and the Unexplored Politics of Residual Emissions', Energy Research & Social Science 98 (2023): 103035, https://doi.org/10.1016/j.erss.2023.103035

removal activity. Below are four principles, set out by Tanzer and Ramirez,[6] 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 GHG 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.

**The 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.

**The NEGEM vision**

The NEGEM project has articulated a shared medium-to-long-term vision (years 2030-2040, and 2050, respectively), projecting a desirable outcome that focuses on sustainable NETPs potentials and their role in contributing to climate action and targets. The vision also aims to inform European and global policymaking, as well as strategy development of NETPs. The project has been running since June 2020 and has published a significant amount of multidisciplinary scientific results (Deliverable 8.3).

Based on these results (running up to January 2024) NEGEM has devised three storylines that explore the technical, environmental, and social constraints and benefits related to various NETPs. All storylines aim for 1.5 °C mitigation target during this century, allowing for intermediate overshoot. The storylines are listed as: "Advanced technology and global markets (1.5C-Tec); Nature conservation and biodiversity (1.5C-Env)"; "Security and self-sufficiency (1.5C-Sec)" (Deliverable 8.2). NEGEM has combined these to create a robust scenario, feeding into the final NEGEM vision. Naturally, this vision only describes potential trajectories on how the future might unfold; the scenarios are not to be interpreted as forecasting the future, but as providing scale and understanding on the magnitude of solutions needed.

[6] Samantha Eleanor Tanzer and Andrea Ramírez, 'When Are Negative Emissions Negative Emissions?', Energy Environ. Sci. 12, no. 4 (2019): 1210–18, https://doi.org/10.1039/C8EE03338B

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 counts or not 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. To do so, the handbook is split into two parts: the first discusses a variety of concepts relevant to CDR, while the second provides a visually engaging review of the different NETPs, addressing key facts, advantages and disadvantages, constraints, future research, and recommendations. While the handbook is based on the results and findings of the numerous work packages within the NEGEM project, it also draws on additional sources to present both a wider overview and more detailed information.

# 1 Key concepts for carbon dioxide removal

## 1.1 Accounting

**Key messages**

Accurate carbon accounting is essential for robustly quantify net removals and managing impacts so as to ensure CDR does not add pressure to planetary boundaries. In principle, accounting can seem 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.

**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 individual entities to meet regulatory reporting obligations under the Corporate Sustainability Reporting Directive[7] (CSRD, 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.[8]

**What carbon accounting relevant for CDR?**

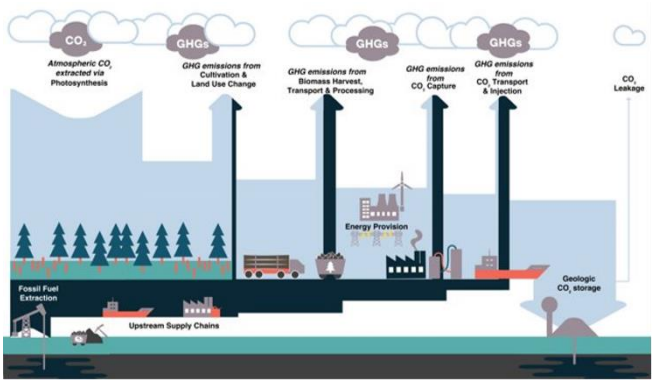
The climate benefit of carbon dioxide removal arises from extracting $CO_2$ from the atmosphere and storing it permanently, thus reducing the amount of $CO_2$ that is in the atmosphere. This means that each CDR approach must physically remove and store more $CO_2$ than the GHGs emitted in the removal 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 counted from 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

[7] 'Directive (EU) 2022/2464 of the European Parliament and of the Council as of 14 December 2022, Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards Corporate Sustainability Reporting', Official Journal L 322/15, 14 December 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022L2464

[8] Understood here as emissions factors, defined by the USA Environmental Protection Agency as: "An **emissions factor** is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant", accessed 28/3/2024, https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification

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.



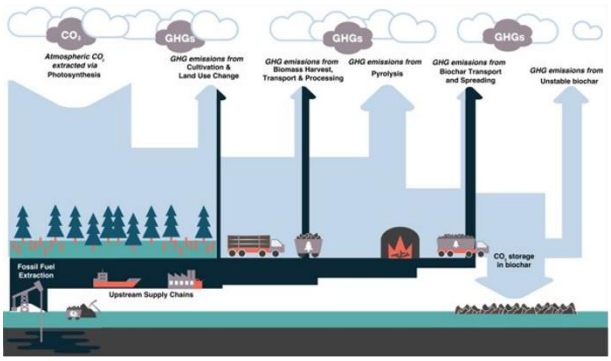

**BioCCS**

**Source** atmospheric $CO_2$ captured by photosynthesis

**Sink** geological storage

**System** *Biomass* → biomass cultivation, harvesting/transport/processing/ conversion/use

*CCS* → $CO_2$ capture, transport storage




**Biochar**

**Source** atmospheric $CO_2$ captured by photosynthesis

**Sink** pyrolysed biomass

**System** *Biochar production* → cultivation, harvesting/transport/processing/ conversion/use

*Biochar application* → transport, spreading, degradation

*Figure 2 Two examples of CDR systems for BioCCS (top) and biochar (bottom), which define the source, sink and system. Fossil fuel emissions sources along the entire value chain are also identified. Figure modified from Tanzer et al. 2022.*[9]

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 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.

[9] Samantha Eleanor Tanzer et al., 'Global Governance of NETPS - Global Supply Chains and Coherent Accounting', 30 November 2022, https://www.negemproject.eu/wp-content/uploads/2023/01/D6.3-Global-Governance-of-NETPs.pdf

- **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, that have a high reversal risk, are accounted separately to 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 LCA 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.

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 $CO_2$eq" 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,[10] but are not in widespread use, and still leaves the timing unclear.

**<u>Challenges for accurate and coherent carbon accounting</u>**

1. 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.

[10] Tuomas Helin et al., 'Approaches for Inclusion of Forest Carbon Cycle in Life Cycle Assessment - a Review', GCB Bioenergy 5, no. 5 (2013): 475–86, https://doi.org/10.1111/gcbb.12016; Miguel Brandão et al., 'Quantifying the Climate Change Effects of Bioenergy Systems: Comparison of 15 Impact Assessment Methods', GCB Bioenergy 11, no. 5 (2019): 727–43, https://doi.org/10.1111/gcbb.12593

2. Transboundary accounting between countries will be needed as often different steps in a CDR system occur in 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.
3. Some CDR approaches have highly dispersed storage of $CO_2$ or capture processes that are slow and difficult to measure directly. This means that there is higher uncertainty in the amount of carbon captured and stored.
4. Use of partially recycled materials and mixed waste with carbon of both biogenic and fossil origin makes it difficult to determine the source of carbon emissions and if a net removal of $CO_2$ has indeed 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 and standard practice. 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 resulted in additional spending to achieve the carbon stored, rather than relying on passive and ongoing activities. Carbon-related financial flows were needed to make this activity economically viable. This type of additionality is secondary and is used to match 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 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 that was never under threat of deforestation or soil that had to be restored under nature protection laws. 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.

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

**Key messages**

Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS) are frequently conflated and misrepresented as forms of Carbon Dioxide Removal (CDR). However, CCS and CCU are technological pathways, whereas CDR is one of the potential outcomes of those pathways. CCS and CCU have different climate mitigation roles, with varying degrees of permanence and impacts on the climate system and 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. With 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 systems costs and lowering overall efficiency of the system. A system with carbon capture demands additional energy and material inputs to produce the same final 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.

Just 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 the $CO_2$ fate.

**What are 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.[11] $CO_2$ 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)[12] 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

[11] Bellona Report 'Clearing Conflations on Carbon Capture Terminologies', 2024, accessed 28 March 2024, https://eu.bellona.org/publication/clearing-conflations-on-carbon-capture-terminologies/

[12] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide (2009), Official Journal L140/114. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031

from renewable sources,[13] 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 $CO_2$.[14] Moreover, 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.[15]

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.[16] 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.

**Why are CCU and CCS relevant for CDR?**

CCU and CCS are frequently conflated and misrepresented as forms of CDR. These need to be 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.

[13] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast) (2018). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018L2001-20181221&qid=1647270042844

[14] Bellona Europa, "The Net Zero Industry Act: Unprecedented step in the right direction", 22 February 2024, https://eu.bellona.org/2024/02/22/the-net-zero-industry-act-unprecedented-step-in-right-direction/

[15] EC, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Towards an ambitious Industrial Carbon Management for the EU", COM(2024) 62 final, 6 February 2024 https://energy.ec.europa.eu/system/files/2024-02/Communication_-_Industrial_Carbon_Management.pdf

[16] Sara Budinis et al., 'An Assessment of CCS Costs, Barriers and Potential', Energy Strategy Reviews 22 (2018): 61–81, https://doi.org/10.1016/j.esr.2018.08.003

CCS and CCU from industrial or fossil sources do not extract past emissions from the air but prevent new ones from happening. These pathways are energy-intensive, with CCS typically consuming 1-3 MWh/tonne of $CO_2$,[17] 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.

Despite these energy requirements, 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.[18] 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; it 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 also needed for some CDR approaches, without which we will not be able to reach our climate goals.[19]

[17] data based on IEA (2022) Direct Air Capture and IEA (2023) The Oil and Gas Industry in Net Zero Transition

[18] Bellona Europa/E3G, 'Carbon Capture and Storage Ladder: Assessing the Climate Value of CCS Applications in Europe', accessed 28 March 2024. https://bellona.org/publication/carbon-capture-and-storage-ladder-assessing-the-climate-value-of-ccs-applications-in-europe

[19] Bellona Europa, 'Carbon Capture and Storage: A Crucial Piece of The Puzzle in Industry's Path To Net-Zero', June 2023, accessed 28 March 2024. https://network.bellona.org/content/uploads/sites/3/2023/06/Bellona-Europa-CCS-Explainer-2023-6.pdf

### *1.3 The carbon cycle*

**Key message**

Carbon dioxide removal, by definition, removes this greenhouse gas from the atmosphere and permanently stores in away from the atmosphere, either on land, underground or in the oceans. 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 37000 Gt of carbon is stored in the oceans, with a further 1700 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).

The stored 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

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.

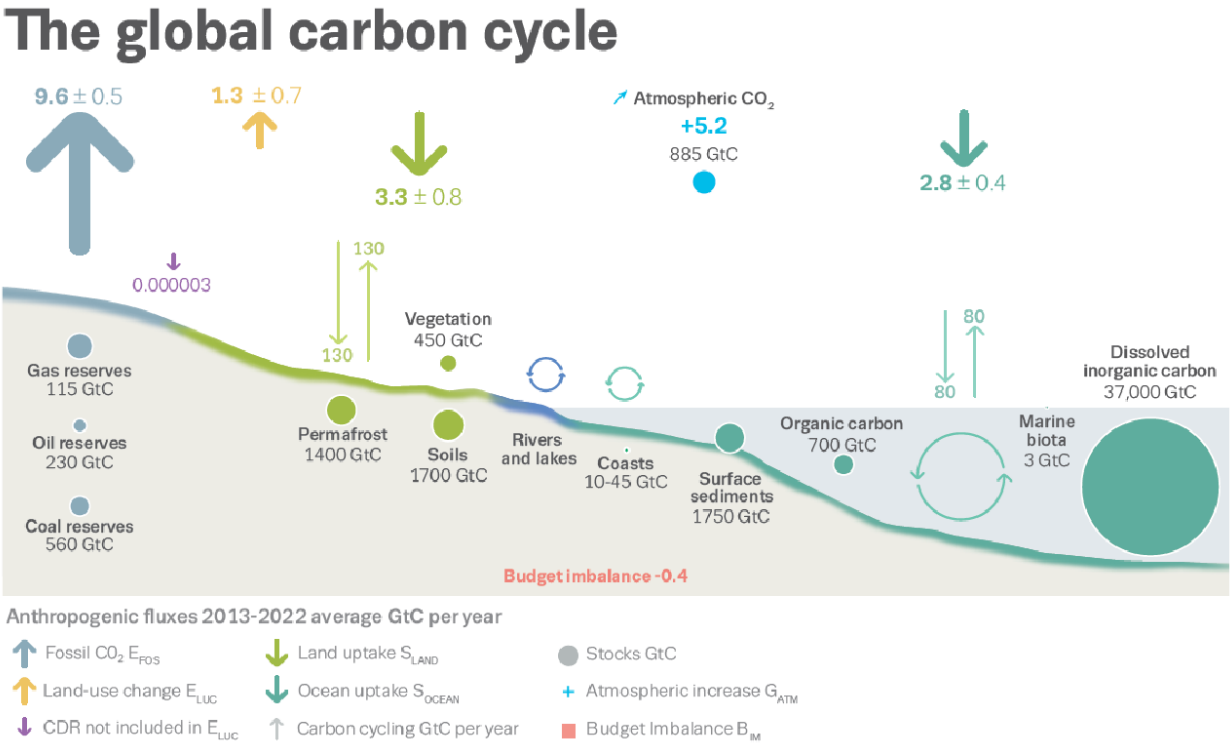



*Figure 3 Overview of the carbon cycle. Circles indicate the global average carbon reservoirs in Gt C (circles) with the arrows representing carbon flows in Gt C yr$^{-1}$, including uncertainty of 1 standard deviation. Source: Global Carbon Budget 2023[20].*

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).[21]

**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**.** 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 $CO_2$.[22] Hence, an overshoot[23] scenario (i.e. where $CO_2$ concentrations temporarily exceed an agreed limit and excess

[20] Pierre Friedlingstein et al., 'Global Carbon Budget 2023', Earth System Science Data 15, no. 12 (2023): 5301–69, https://doi.org/10.5194/essd-15-5301-2023

[21] Friedlingstein et al., 'Global Carbon Budget 2023'

[22] Kirsten Zickfeld et al., 'Asymmetry in the Climate–Carbon Cycle Response to Positive and Negative CO2 Emissions', Nature Climate Change 11, no. 7 (2021): 613–17, https://doi.org/10.1038/s41558-021-01061-2 ; Kirsten Zickfeld, Andrew H MacDougall, and H Damon Matthews, 'On the Proportionality between Global Temperature Change and Cumulative $CO_2$ Emissions during Periods of Net Negative $CO_2$ Emissions', Environmental Research Letters 11, no. 5 (2016): 055006, https://doi.org/10.1088/1748-9326/11/5/055006

[23] The IPCC define overshoot pathways as "pathways that exceed the stabilization level (concentration, forcing, or temperature) before the end of a time horizon of interest (e.g., before 2100) and then decline towards that level by

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 (TCRE)[24] 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.[25] 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.

that time. Once the target level is exceeded, removal by sinks of greenhouse gases is required". See p. 555: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_AnnexI.pdf

[24] The IPCC define TCRE as "(t)he transient global average surface temperature change per unit cumulative $CO_2$ emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative $CO_2$ emissions (the fraction of the total $CO_2$ emitted that remains in the atmosphere, which is determined by carbon cycle processes) and on the transient climate response (TCR)". See p. 559: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_AnnexI.pdf

[25] Sebastian Sonntag et al., 'Quantifying and Comparing Effects of Climate Engineering Methods on the Earth System', Earth's Future 6, no. 2 (2018): 149–68, https://doi.org/10.1002/2017EF000620

### *1.4 Carbon market mechanisms*

**Key messages**

Carbon markets put a price and/or limit on emissions. Currently, no robust market-based mechanism exists to comprehensively tackle removals.

There are two predominant types of carbon market mechanisms, namely emission trading systems (ETS) and carbon crediting mechanisms. It cannot be scientifically proven that one carbon credit reliably neutralises or counterbalances one tonne of $CO_2$ emitted.

The responsibility to fund removals should not be left to voluntary markets. Markets tend not to separate between natural and technological approaches, are likely to favour the cheapest option and do not favour diverse portfolios.

**What are carbon market mechanisms?**

Carbon markets are market-based instruments used to tackle the climate change crisis. They aim to reduce GHGs by putting a price and/or a limit on emissions, primarily carbon dioxide. Currently, no robust market-based mechanism exists to comprehensively tackle removals, with the UNFCCC negotiations on Article 6 of the Paris Agreement still on-going. The two most common carbon market systems, explained in further detail below, 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 commonly found in global voluntary carbon markets, which are dominated by projects geared towards reducing emissions, but also include projects aiming to increase carbon sequestration in the land sink. It is questionable whether either market system could ensure that carbon removal activities are carried out in a socially just manner, whilst ensuring alignment with the physical climate impact (also referred to as physical credibility).[26]

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. In the EU ETS, this cap takes the form of allowances or pollution permits, which companies buy and sell on the open market and subsequently trade with one another. The reduction targets, set by EU policymakers, are achieved by gradually lowering this cap. Given that the system is based on the 'polluter pays principle', the costs of pollution should be borne by those who create it, meaning companies purchase these allowances in order to pollute. However, 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[27][28] This also makes them ill-suited to support a portfolio approach of CDR approaches that have different costs.

[26] Allanah Paul et al., 'Who Should Use NETPS? Managing Expectations for NETP Demand: Considerations for Allocating Carbon Dioxide Removals', 2023, https://network.bellona.org/content/uploads/sites/6/2023/12/Who-Should-Use-NEPTs.pdf

[27] Elisa Martellucci et al., 'EU ETS 101 A beginner's guide to the EU's Emissions Trading System', February 2022, p.4 https://carbonmarketwatch.org/wp-content/uploads/2022/03/CMW_EU_ETS_101_guide.pdf

[28] Fabiola de Simone and Wijnand Stoefs, 'The bare necessities: essential principles to design sensible carbon removal policies', November 2023, p.11 https://carbonmarketwatch.org/wp-content/uploads/2023/12/The-bare-necessities-essential-principles-to-design-sensible-carbon-removal-policies-1.pdf

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. This is problematic as the project from which the credit stems may: no longer be under management, have released any carbon stored in vegetation or soils, or stopped reducing emissions. 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 can be made. While all credits require projects, not all projects generate credits, meaning, projects can also serve other, non-climate focused purposes.

**Issues with carbon market mechanisms**

In carbon market mechanisms, it is essential for the 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.

Crediting schemes often stem from nature-based projects, which are difficult to do MRV on, vulnerable to reversals, and are therefore likely to only store carbon temporarily. If poorly managed, they might even become a source of emissions. The REDD+ forestry projects, for instance, 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.[29] Such projects did not deliver climate benefits that are equivalent to the climate damage they were meant to offset, undermining environmental integrity.

Another crucial point 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% less impact on the climate than a tonne emitted[30] due to interaction with land and ocean carbon stocks[31] - and each tonne removed needs to be monitored and kept out of the atmosphere indefinitely. This false equivalence deters polluters from addressing their emissions as it allows them to buy credits and avoid reducing their carbon footprint.

**NEGEM Project**

[29] See for example: Patrick Greenfield, "Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows," *The Guardian,* January 2023, https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe; Nina Lakhani, "Revealed: top carbon offset projects may not cut planet-heating emissions," *The Guardian,* September 2023 https://www.theguardian.com/environment/2023/sep/19/do-carbon-credit-reduce-emissions-greenhouse-gases

[30] IPCC, 'Summary for Policymakers: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change', 2021, p.30, https://doi.org/10.1017/9781009157896.001

[31] Kirsten Zickfeld et al., 'Asymmetry in the climate–carbon cycle response to positive and negative $CO_2$ emissions' *Nature Climate Change* 11, (2021), 613–617, https://doi.org/10.1038/s41558-021-01061-2

The NEGEM project studied the commercialisation of NETPs as part of its work programme; "current deployment is supported by a wide range of incentive mechanisms, many of which (such as direct government financing for the demonstration of commercial-scale NETP projects) are ill-suited to large-scale commercialisation."[32] The mechanisms do not favour the creation of a balanced portfolio for achieving net zero emissions and are significantly under-funded considering that between €4.8 and €6.7 billion will be needed to scale up removals by 2030, with a potential increase to up to €30 billion by 2050.[33] Indeed, engineering solutions such as DACCS and BioCCS are expensive, although they have the potential to store carbon for millennia. This is contrary to land-based solutions, which are cost-effective, yet present a high risk of carbon leakage, evoke climate feedbacks, and have limited global capacity and potential to support ambitious climate goals. Therefore, despite their cost-effectiveness, these issues would lead to significant reputational and financial risks for any actor relying on biological carbon sequestration to offset on-going fossil fuel usage.

A suggestion that was put forward in the NEGEM project was to move towards "progressive offsets" otherwise known as prosets. Prosets seek to jointly incentivise the development of high-potential high-reliability negative emissions technologies (typically engineered solutions) as well as limited-potential low-cost measures (such as many typical nature-based climate solutions).[34] They can be viewed as composite carbon credits in which the fraction of carbon allocated to geological-timescale storage options increases progressively, reaching 100% by the target net zero date, generating predictable demand for effectively permanent $CO_2$ storage while making the most of the near-term opportunities provided by nature-based climate solutions, all at an affordable cost to the purchaser.[35]

**Alternative solution**

However, markets may not be a suitable tool for funding carbon removals and land sequestration approaches. This is especially the case if no separation is created between engineering solutions, natural approaches and emission reductions within the particular framework.[36] As explained above, market rationalism will always prioritise the cheapest option, meaning a framework without separation will likely prioritise land-based approaches, which are inherently vulnerable to human and natural disturbances and are therefore prone to rereleasing sequestered carbon into the atmosphere. This will also limit the possibility of adopting a wide CDR portfolio, necessary to reduce the risks associated with relying on one singular approach and to maximise the overall effectiveness of carbon removal and sequestration efforts.

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[32] Conor Hickey and Myles Allen, 'Quantitative survey of commercialisation mechanisms', November 2021, p.3, https://www.negemproject.eu/wp-content/uploads/2022/04/D2.1-Quantitative-survey-of-commercialisation-mechanisms.pdf

[33] Conor Hickey and Myles Allen, 'Quantitative survey of commercialisation mechanisms'

[34] Eli Mitchell-Larson and Myles Allen, 'Interactions and trade-offs between nature-based and engineered climate change solutions', 2021, p.3, https://www.negemproject.eu/wp-content/uploads/2021/11/D-2.2-Interactions-and-trade-offs-between-nature-based-and-engineered-climate-solutions.pdf

[35] Eli Mitchell-Larson and Myles Allen, 'Prosets: a new financing instrument to deliver a durable net zero transition', *Climatic Change* 174 (2022), https://doi.org/10.1007/s10584-022-03423-x

[36] Fabiola de Simone and Wijnand Stoefs, 'The bare necessities: essential principles to design sensible carbon removal policies', Carbon Market Watch, November 2023, p.30, https://carbonmarketwatch.org/wp-content/uploads/2023/12/The-bare-necessities-essential-principles-to-design-sensible-carbon-removal-policies-1.pdf

As such, a possible solution is to opt for a contribution claim model. This model allows companies to 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.[37] 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.[38] Given the need to accelerate the ecological transition and to prevent companies from relying on low-quality carbon credits - as opposed to implementing deep, rapid, and sustained emissions cuts - opting for a contribution model might foster the reductions we so desperately need. Crucially, the contribution model will uphold the three core principles underpinning climate policy: the precautionary principle, the do no (significant) harm principle, and the primacy of emissions reductions.

[37] Gilles Dufrasne and Jonathan Crook, 'Carbon Markets 101: The ultimate guide to climate-based market mechanisms', February 2024, p.27 https://carbonmarketwatch.org/wp-content/uploads/2024/02/101-report-layout-carbon-markets-230224.pdf

[38] Gilles Dufrasne and Jonathan Crook, 'Carbon Markets 101: The ultimate guide to climate-based market mechanisms', p.27

### 1.5 Efficiency of carbon dioxide removal

**Key message**

CDR efficiency refers to how much $CO_2$ is emitted from the activity (i.e. "leaked") compared 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.[39] 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.

$$\textbf{CDR efficiency} = \frac{\text{Amount of } CO_2 \text{ stored} - CO_2 \text{ leaked in supply chain}}{\text{Amount of permanently stored } CO_2}$$

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-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*

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, which is based on the trajectories in Chiquier et al.[40]

[39] Solene Chiquier et al., 'A Comparative Analysis of the Efficiency, Timing, and Permanence of $CO_2$ Removal Pathways', Energy & Environmental Science 15, no. 10 (2022): 4389–4403, https://doi.org/10.1039/D2EE01021F

[40] Solene Chiquier et al., 'A Comparative Analysis of the Efficiency, Timing, and Permanence of $CO_2$ Removal Pathways'

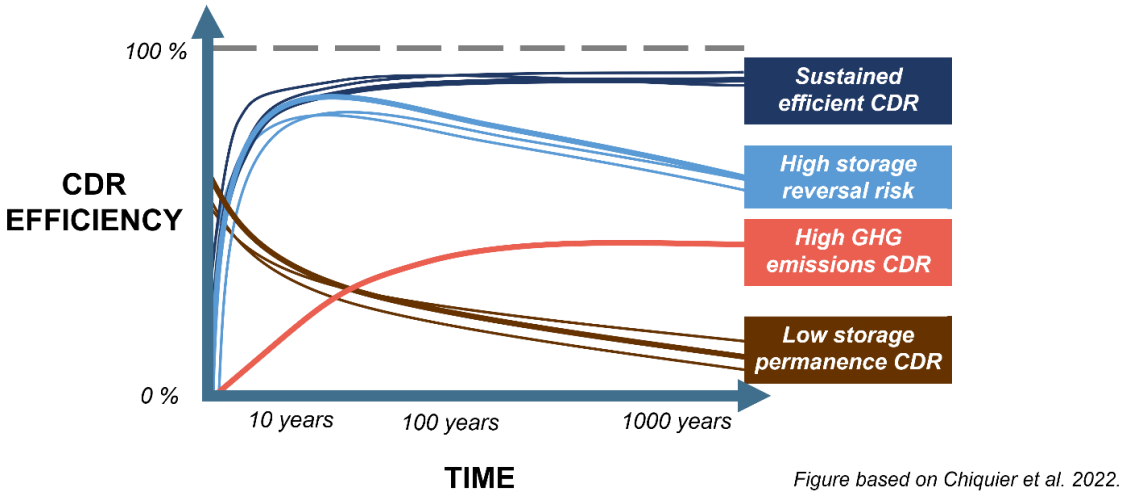



*Figure 4 CDR efficiency over time for a range of different CDR types, based on Chiquier et al. 2022.*

### *1.6 Modelling*

**Key message**

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

Three type of model analyses were applied in the H2020 NEGEM research consortium:

1. Life cycle assessment
2. Cost-optimization in the integrated assessment models, TIMES-VTT
3. Assessment of environmental constraints in the process-based biosphere model, LPJmL

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 (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.

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 BECCS 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 | Objective | Assumptions | Major limitations | Advantages |
|---|---|---|---|---|
| *Life cycle assessment* | Compare sustainability performance of different CDR approaches on a per tonne $CO_2$ removed basis | Average parameters of a CDR approach used (not project specific data) | 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. | Many different CDR approaches can be analysed on their emissions and resource use impacts across their entire lifecycle |
| *Demand driven (e.g. IAMs)* | 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. | Assumptions on the energy system, CDR technologies, population and GWP growth, etc. | 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. | 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 |
| *Process-based biosphere model* | Quantify sustainable biophysical potential of biomass-based CDR with feedstock production on uncultivated land and assess environmental pressures from rededicating pastureland to NETPs | Biomass plantation coverage expands outside agricultural land without transgression of terrestrial Planetary Boundaries or rededication of pastureland to NETPs | Only biogeochemical assessment with no socioeconomic considerations, global technical efficiencies used (not project specific) | Simulates biomass growth and ecosystem impacts at both the global and local scale. |

*Table 1 Overview of modelling approaches used in the NEGEM project to indicate the kinds of objectives, limitations, and advantages to each approach.*

### 1.7 Monitoring, Reporting, Verification, Liability (MRVL)

**Key messages**

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.

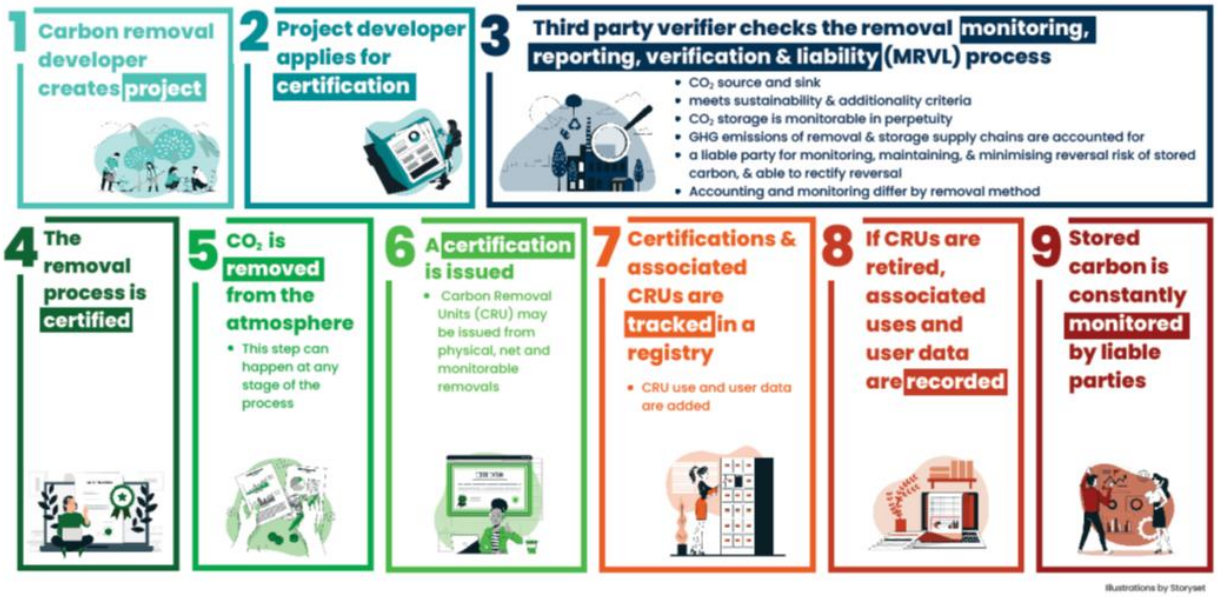



*Figure 5 "How to build a robust framework for the certification of high-quality carbon removals", reproduced with permission from Carbon Gap/Clean Air Task Force/Bellona.*

#### 1.7.1 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" concept page). 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.

### *1.7.2 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.

### *1.7.3 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.

### *1.7.4 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 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.

### 1.8 Permanence

**Key messages**

Permanence of carbon sequestration is a defining principle of carbon removal. For carbon storage to be viewed as permanent, carbon storage must last long enough to meaningfully contribute to climate action. That means sequestered carbon cannot be re-emitted within a timeframe that allows it to contribute 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 critical environmental objectives, such as ecosystem degradation and loss of biodiversity.

There are various definitions of permanence in policy, voluntary carbon markets and scientific research.[41] In the NEGEM project, permanence has been defined as storage lasting at least a few centuries.[42] 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.[43] 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,[44] and about 20% remains for longer than 10,000 years.[45] The rest of the carbon is taken up by ocean and land sinks (see concept page on the "The carbon cycle"). 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

[41] While the IPCC makes use of the term durable or durability, this report shall use the term 'permanence'.

[42] Wijnand Stoefs, 'Principles for Carbon Negative Accounting', November 2021, p.10 https://www.negemproject.eu/wp-content/uploads/2021/12/D-6.2-Principles-for-carbon-negative-accounting.pdf

[43] Stoefs, 'Principles for Carbon Negative Accounting'

[44] Nils Meyer-Ohlendorf et al., 'EU 2040 Climate Target and Framework: The Role of Carbon Removals', November 2023, p.14, https://www.ecologic.eu/sites/default/files/publication/2023/60028-EU-2040-Removals-web.pdf

[45] Danny Cullenward, 'A Framework for assessing the climate value of temporary carbon storage', September 2023, p.14, https://carbonmarketwatch.org/wp-content/uploads/2023/09/FINAL-CMW-version-of-temporary-storage-paper.pdf

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 Direct Air Carbon Capture and Storage (DACCS) and Biomass use with carbon capture and storage (BioCCS) can be considered permanent provided underground storage reservoirs are successfully sealed. Further, mineral carbonation used in enhanced weathering has an expected storage time of more than 10,000 years.[46] 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, the stored carbon in biochar and in enhanced weathering is diluted in the environment, eventually across reservoirs on land, but also in the ocean, which over time 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, biogenic stores are in more direct contact with the atmosphere. Additionally, the 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.[47]

[46] Cullenward, 'A Framework for assessing the climate value of temporary carbon storage', p.13

[47] These are defined by the IPCC as "Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation." See: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_AnnexI.pdf

### *1.9 Planetary boundaries*

**Key messages**

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 point 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 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"[48] 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.[49]

Researchers have identified nine processes that are "critical for maintaining the stability and resilience of the Earth system as a whole".[50] 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.[51] Quantification is possible for individual boundaries, but the interaction and combined response between boundaries is an area of active research.

[48] Johan Rockström et al., 'A Safe Operating Space for Humanity', *Nature* 461, no. 7263 (2009): 472–75, https://doi.org/10.1038/461472a
[49] Johan Rockström et al., 'A Safe Operating Space for Humanity'
[50] Katherine Richardson et al., 'Earth beyond Six of Nine Planetary Boundaries', *Science Advances* 9, no. 37 (2023), https://doi.org/10.1126/sciadv.adh2458
[51] Katherine Richardson et al., 'Earth beyond Six of Nine Planetary Boundaries',

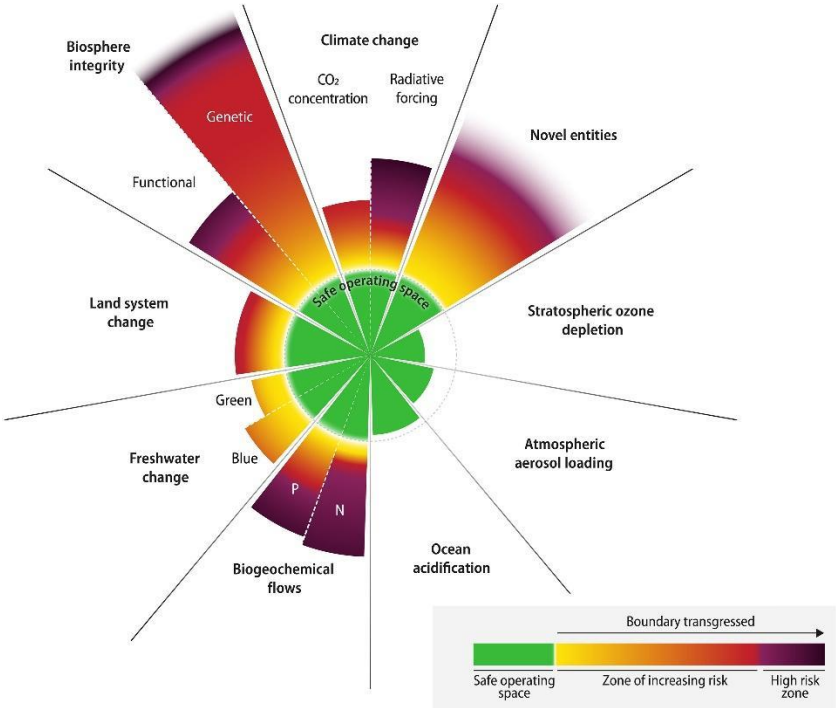



*Figure 6 The Planetary Boundaries Framework. Licenced under CC BY-NC-ND 3.0 (Credit: Azote for Stockholm Resilience Centre, Stockholm University).*

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.[52] The Doughnut theory of Economics[53] 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.[54]

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

[52] See for example," A safe operating space for New Zealand/Aotearoa – Translating the planetary boundaries framework", https://environment.govt.nz/assets/Publications/Files/a-safe-operating-space-for-nz-aotearoa.pdf or "Towards a Safe Operating Space for the Netherlands" https://www.pbl.nl/sites/default/files/downloads/Towards_a_safe_operating_space_for_the_Netherlands_-_3333.pdf

[53] https://doughnuteconomics.org/about-doughnut-economics

[54] X. Lan, P. Tans, and K. W. Thoning, 'Trends in Globally-Averaged $CO_2$ Determined from NOAA Global Monitoring Laboratory Measurements', Version 2024-03, accessed 26 March 2024, https://doi.org/10.15138/9N0H-ZH07

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.

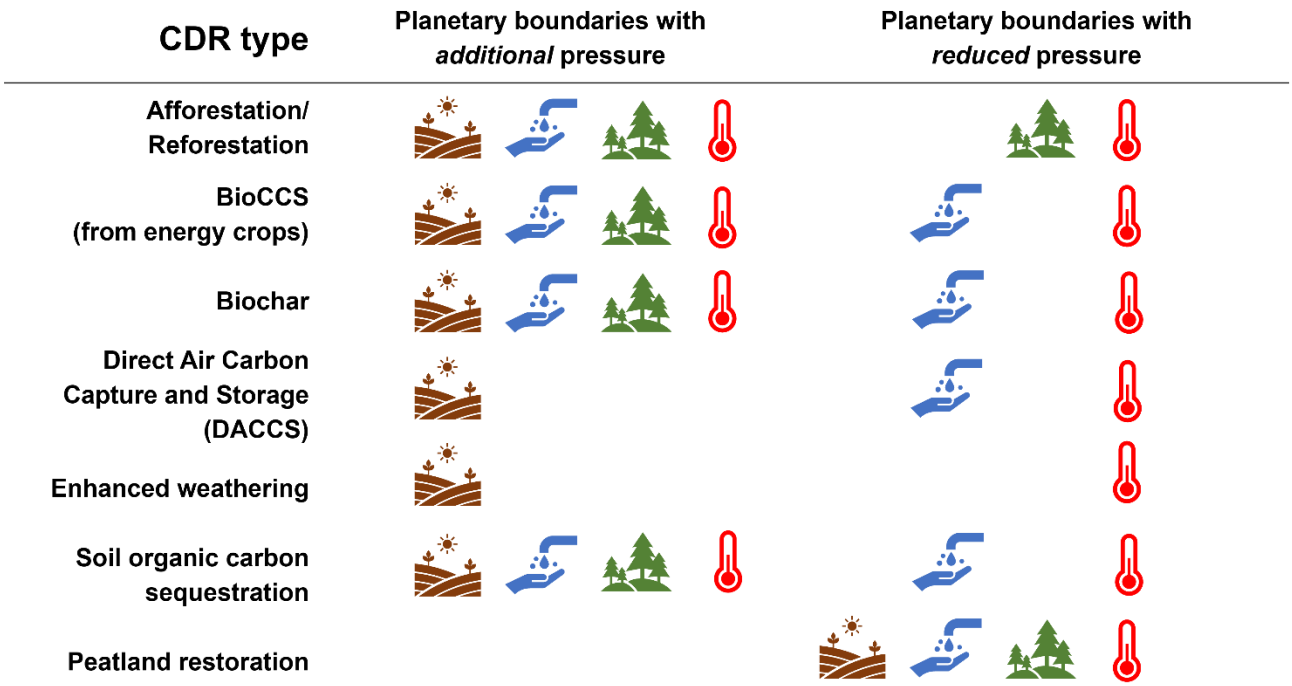



*Figure 7 Potential interaction between CDR project types and planetary boundaries indicating potential trade-offs and co-benefits of each activity. Brown icon = land system change, Blue icon = freshwater use and nitrogen flows, Green icon = biosphere integrity (net primary production + biodiversity), 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.[55] 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

[55] Constanze Werner et al., 'Global Assessment of NETP Impacts Utilising Concepts of Biosphere Integrity', 31 May 2023, https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM_D3.3_Global-assessment-of-NETP-impacts-utilising-concepts-of-biosphere-integrity.pdf; Johanna Braun et al., 'Global NETP Biogeochemical Potential and Impact Analysis Constrained by Interacting Planetary Boundaries', 31 May 2022, https://www.negemproject.eu/wp-content/uploads/2023/05/D-3.2-Global-NETP-biogeochemical-potential.pdf; Johanna Braun et al., 'Global Impacts of NETP Potentials on Food Security and Freshwater Availability, Scenario Analysis of Options and Management Choices', 31 May 2023, https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM_D3.7_Global-impacts-of-NETP-potentials-on-food-security.pdf; Constanze Werner et al., 'Report on Synoptic Assessment of Global Theoretical NETP Potentials', 31 October 2023, https://www.negemproject.eu/wp-content/uploads/2023/12/D3.10-Report-on-synoptic-assessment-of-global-theoretical-NETP-potentials.pdf

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."[56]

[56] Braun et al., 'Global NETP Biogeochemical Potential and Impact Analysis Constrained by Interacting Planetary Boundaries'.

### *1.10 Public perception*

**Key messages**

Understanding stakeholder perception is necessary to secure the social license to operate to implement NETPs, as well as to foster effective dialogue, decision-making and policy on the matter.

Factors such as cost per tonne of $CO_2$ captured associated with these technologies, permanence of the $CO_2$ captured, type of storage, resource use, and project proponent influence stakeholder perception of NETPs.

The optimal bundle was deemed to: use nature-based solutions, have a permanence duration of over 1000 years, cost 50€/t$CO_2$ captured, be proposed by an environmental NGO, and use high energy and water but with low impact on land. However, permanence and resource use emerge as the important dimensions when considering NETP implementation.

While perceptions should not be understood as static and crystallized but as dynamic and evolving via discussion, the narrative used when conveying information on NETPs, and the value-sets to which stakeholders adhere to affect perception and acceptability of NETPs. Similarly, a country's $CO_2$ emissions and its capacity to implement also play a role in influencing perceived fairness and acceptability.

Policymakers ought to take these differences into account when conveying policy on CDR implementation. Similarly, communication amongst often-clashing sectors could be eased when the preferred narrative of the opposing stakeholder is adopted.

Understanding stakeholder perception on the associated risks and benefits with each NETP is essential to foster effective dialogue, decision-making and policy development on the topic. It also feeds into the social licence to operate (SLO), meaning if CDR is perceived negatively, it will be far more challenging to receive public support, secure the SLO, and ultimately implement CDR at scale. Stakeholder perception of NETPs was assessed by a series of surveys within the NEGEM project. This page seeks to convey the NEGEM results on how NETPs are perceived, and which key factors should be considered when developing CDR policy. The page is split into two parts. The first looks at the five dimensions the surveys analysed when investigating stakeholder perception on NETPs, while the second presents an overview on the importance of framing of NETPs and ethical values within sectors, as well as perceived fairness and acceptability over NETP implementation.

**Part 1: Five dimensions**

Part of the NEGEM work programme assessed the most valued NETP features across different stakeholder profiles, and thus their relative importance in shaping stakeholder preferences. To do so, the research undertook a conjoint analysis study, a research method designed to dissect the preferences of participants by presenting them with a series of options that vary across a set of defined dimensions.[57] The following five

[57] Deborah Marshall et al. 'Conjoint analysis applications in health – how are studies being designed and reported?', *The Patient Patient-Centered Outcomes Research* 3, no. 4 (2010), 249-256 https://doi.org/10.2165/11539650-

dimensions were assessed: cost per ton of $CO_2$ captured associated with these technologies, permanence of the $CO_2$ captured, type of storage (biological or geological), resource use, and project proponent.[58]

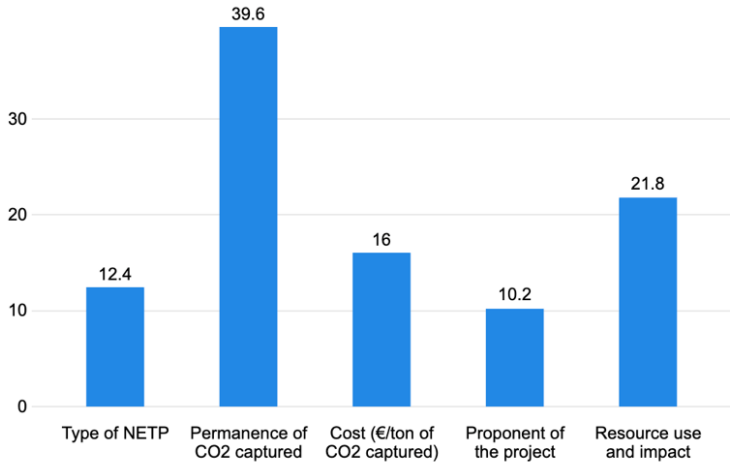



*Figure 8 Relative perceived importance of five dimensions of CDR based on a stakeholder survey (NEGEM deliverable D5.6).*[59]

Figure 7 illustrates the importance given to each attribute in the decision-making process. As shown, the permanence of the $CO_2$ captured dominates decision-making importance, amounting to 39.6% of the weight. This is followed by resource use and impact (21.8%), cost (16%), the type of NETP (12.4%), and finally, the project proponent (10.2%).

Other results show:

- a slight preference for nature-based NETPs over technology-based solutions
- a clear preference for higher $CO_2$ permanence levels
- a preference for options with lower costs
- a distinct preference for projects proposed by environmental NGOs, as opposed to those by energy or oil and gas companies (despite this dimension being less influential in the overall decision-making process)
- a preference for high water and energy use with low land impact (59% of respondents) over low energy and water use with high land impact (31%).

By combining these, the optimal NETP project was found to use nature-based solutions, have a permanence duration of over 1000 years, cost 50€ per ton of $CO_2$ captured, be proposed by an environmental NGO, and use high energy and water but with low impact on land.

000000000-00000; Mandy Ryan and Shelley Farrar 'Using conjoint analysis to elicit preferences for health care' *BMJ* 320, no. 7248, (2000), 1530-1533. https://doi.org/10.1136/bmj.320.7248.1530

[58] not yet published: David Reiner et al., 'Final Report of Stakeholder Survey: Solving NETPs Trade-Offs', March 2024

[59] Reiner et al., 'Final Report of Stakeholder Survey: Solving NETPs Trade-Offs'

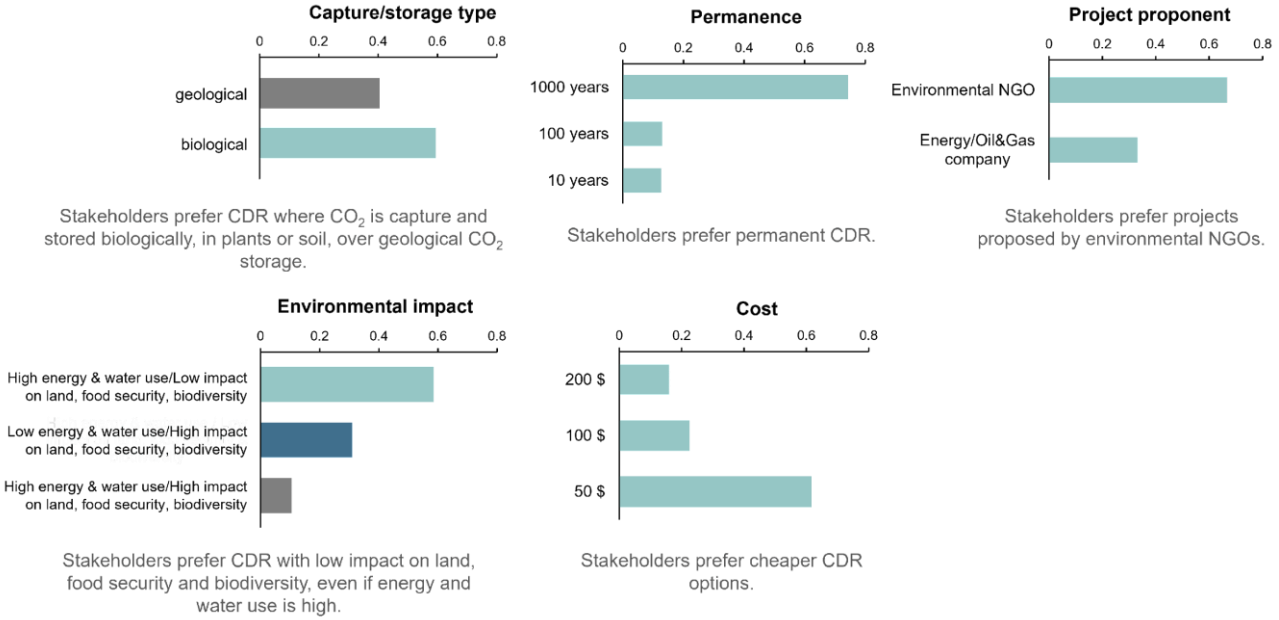



*Figure 9 Stakeholder preferences on CDR type, permanence, environmental impacts, costs, and project proponent, as assessed by the NEGEM project.*[60]

These results might at first appear contradictory as nature-based solutions are not permanent given their inherent vulnerability to natural and anthropocentric factors. However, conceptual preference for natural approaches may be due to the additional co-benefits they provide for the ecosystem, their contribution to the natural cycle and simpler implementation processes. Moreover, the results show that cheaper CDR options are preferred, which also conflicts with the preference for permanent solutions (Figure 8). While these may become cheaper as technology develops, at present DACCS and BioCCS are the most expensive forms of CDR. Regarding the environmental impact, all NETPs, whether ecological, geological or a mixture of both, bear different impacts. In this sense, it is important to consider the numerous tensions and trade-offs when developing CDR portfolios.

However, a closer study reveals which features from this 'optimal bundle' are deemed more important: the permanence of $CO_2$ capture and the utilisation of resources. It could therefore be inferred that a technology-based NETP that offers relatively high permanence and cost, is proposed by a company, and utilises water and energy resources while minimising land use impacts - a description that best accords to DACCS - might be preferred.

## Part 2: framing and values, perceived fairness and acceptability

### Framing and values

The way in which information on NETPs is framed alters perception and acceptability of these for stakeholders.[61] For context, the pros and cons of NETPs can be framed either through an emotional/moral or scientific/logical sense; the former uses arguments on intergenerational fairness, risks of mitigation deterrence, and biodiversity concerns, whereas the latter highlights data on permanence, estimated costs

[60] Reiner et al., 'Final Report of Stakeholder Survey: Solving NETPs Trade-Offs'

[61] See Sabine Fuss et al., 'Negative emissions—part 2: costs, potentials and side effects', Environmental Research Letters 13 (May 2018) https://doi.org/10.1088/1748-9326/aabf9f

and resource usage.[62] It was found that introducing a scientific framing seemed to foster a positive change in attitude towards NETPs, particularly with the private sector. However, emotional framing only favoured dialogue and understanding for NGOs, a possible explanation being that the private sector is less accustomed to using such language. This suggests that communication amongst these often-clashing sectors could be eased when the preferred narrative of the opposing stakeholder is adopted.[63] It should be noted, however, that the arguments used in each narrative are not necessarily exclusive. For example, carbon storage permanence could be linked to intergenerational fairness by ensuring that carbon removed benefits multiple generations, rather than used as a stop-gap measure of climate change mitigation.

Similarly, the way sectors solve moral dilemmas, whether through a consequentialist or a normative approach, also influences perception.[64] The former is mainly akin to private sector representatives, while the latter is common among NGOs. This ethical framework is at play when, for instance, discussing tensions and trade-offs between NETPs and whether they should be employed solely as removal mechanisms or to promote environmental and social co-benefits. In this vein, proposed solutions often adhere to predefined values.

**Perceived fairness and acceptability**

Lastly, it was also examined how perceptions of the country's $CO_2$ emissions and its capacity to implement NETPs - specifically A/R and DACCS - influences perceived fairness and acceptability towards implementing NETPs.[65] Participants found that it would be fairer and more acceptable if a particular country with high $CO_2$ emissions and sufficient knowledge and resources would implement both NETPs. However, they also found that it would be fairer and more acceptable if a country with high $CO_2$ emissions but less capacity than another country with lower $CO_2$ emissions, would implement NETPs. As such, stakeholders place more importance on the rate of a country's $CO_2$ emissions for NETP implementation on a national level. This is so despite previous efforts to cut $CO_2$ emissions. As to public perception on the role of NETPs in reaching climate goals, stakeholders prioritised reducing $CO_2$ emissions by producing more renewable energy, and behavioural change (less flying and a diet shift). On average, however, participants considered that multiple solutions would be required to mitigate climate change.

**Conclusion**

Perceptions should not be understood as static and crystallised but as dynamic and evolving via discussion. Nuanced understanding of sectoral variation is important to inform policymaking and better understand the contexts within which NETPs would be more likely to be granted and SLO. Different prompts evoke different reactions; depending on the discourse or value-sets in which perceptions are rooted, stakeholders might favour or reject an engagement with NETPs. Stakeholders are relevant not only to advance the research and development and the implementation of NETP-related projects but also to legitimise policies and initiatives

[62] David Reiner et al., 'Stakeholder views on NETP governance' November 2021, https://www.negemproject.eu/wp-content/uploads/2021/12/D-5.3-Stakeholder-views-on-NETP-governance.pdf

[63] Lucrezia Nava et al., "Stakeholder perception of NETPs: The effects of discussion and framing", Lecture, Gothenburg, June 2022, https://www.negemproject.eu/wp-content/uploads/2022/07/Slides-NegEm_final.pdf

[64] David Reiner et al., 'Stakeholder views on the business case for NETPs', 31 May 2022, https://www.negemproject.eu/wp-content/uploads/2022/06/NEGEM_D5.2_Stakeholder-views-on-the-business-case-for-NETPs.pdf

[65] Chieh-Yu Lee et al., 'Public awareness and assessments of NETPs: Results of a series of cross-national public surveys', 30 November 2023 https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D5.5_Public-awareness.pdf

from other stakeholders. In this vein, the EU should cater how it communicates policy to the sensitivities of each sector, moving away from a one-size-fits-all approach. Ultimately, policymakers will need to find a balance and mediate between these opposing approaches to enable a fruitful dialogue among stakeholders.

### *1.11 Separation of activities and the need for separate targets*

**Key messages**

Climate mitigation policy covers a number of activities, namely emission reduction, emission avoidance, permanent carbon removal, and land 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

**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 9). For the foreseeable future, this is the most important type of climate 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 1.1"Accounting") and the EU's Carbon Removal Certification Framework (see Section 1.12 "Status of EU legislation and policy") view permanence as a period lasting at least several centuries. DACCS, BioCCS, enhanced weathering, and potentially certain use case examples of biochar fall under this category. The climate action is physically extracting and permanently storing $CO_2$ out of the atmosphere (Figure 9) 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 can be highly vulnerable to reversals. 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.

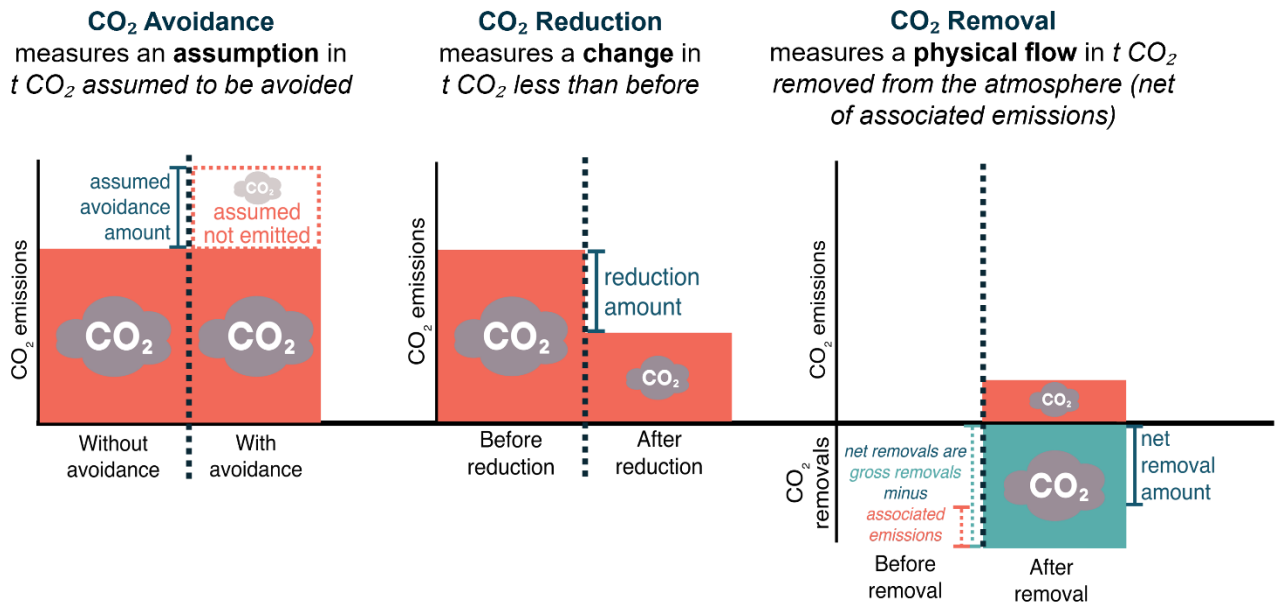



*Figure 10 Difference in net emissions between an avoided emission (left), reduce emission (centre), and a carbon removal (right). Source: Bellona.*

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. 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 to land sequestration, it can play a vital role for 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 increase 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. This means that 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.

**<u>Why are separate targets necessary?</u>**

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.[66] Separation provides many benefits:

- **Avoiding the slowing down or delaying of emission reduction efforts, also known as mitigation deterrence.**[67] Different activities cannot act as a substitute for one another; they are not interchangeable[68] - a removal can never meet reduction obligations, and overreliance on these is risky.[69] 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 sequestration providing excellent co-benefits, and permanent removals extracting residual emissions in hard-to-abate sectors.[70]
- **Avoids equating geological storage and biological sinks thereby preventing misuse or misclassification of vulnerable or temporary storage as 'permanent removals'**.[71] 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.**[72] 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 (100%/net zero or 'climate neutrality') 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, seem very ambitious, but it actually implies an emissions reduction target (gross

[66] Carbon Market Watch, 'Open letter calling for a firewall between carbon emissions, land sequestration and permanent removals in the EU', 8 January 2024, https://carbonmarketwatch.org/wp-content/uploads/2024/01/High-Level-Letter-w_-Logos-signatories-rev.-18_01-1.pdf

[67] Duncan McLaren et al., 'Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions', Frontiers in Climate 1 (2019) https://doi.org/10.3389/fclim.2019.00004

[68] Nils Meyer-Ohlendorf et al., 'EU 2040 Climate and Framework: The Role of Carbon Removals', 29 November 2023, Ecologic Institute, Berlin, p.2 https://www.ecologic.eu/sites/default/files/publication/2023/60028-EU-2040-Removals-web.pdf

[69] Nils Meyer-Ohlendorf et al., 'EU 2040 Climate and Framework: The Role of Carbon Removals'

[70] To be defined in a realistic and dynamic way; what is known as 'hard-to-abate' today might not be in a few years or decades as new technologies or practices and behavioural changes take hold. See Fabiola de Simone et al. 'How do NETPs fit in existing climate frameworks?', 31 August 2023, p.27, https://www.negemproject.eu/wp-content/uploads/2023/09/NEGEM-D6.1-NETPs-in-existing-climate-frameworks.pdf

[71] Nils Meyer-Ohlendorf et al., 'EU 2040 climate architecture', November 2023, Ecologic Institute, Berlin, p.12 https://www.ecologic.eu/sites/default/files/publication/2023/60028-2040-Climate-Architecture-report.pdf

[72] Fabiola de Simone et al. 'How do NETPs fit in existing climate frameworks?', p.6

target) of up to 82%.[73] The remainder of the net-90% consists of temporary storage (some of which is very vulnerable such as soil carbon sequestration) and permanent removals. Further, the 2040 strategy, calls for an annual removal or sequestration target of up to 400 Mt carbon dioxide equivalent ($CO_2e$) by 2040, without unpacking or disaggregating this goal in the communication itself.[74] This conflates permanent removals and storage in soils or biomass, despite having very different impacts on the climate.

[73] Khaled Diab, 'EU's underwhelming 2040 climate target shifts responsibility to future generations', Carbon Market Watch, February 2024, https://carbonmarketwatch.org/2024/02/06/eus-underwhelming-2040-climate-target-shifts-responsibility-to-future-generations/

[74] EC, 'Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Securing our future, Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society', COM(2024) 63 final, 6 February 2024, p.6 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024DC0063

### *1.12 Status of EU legislation and policy*

**Key messages**

EU legislation relevant to CDR and natural sequestration is: 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 others, it does not provide for separate targets and misses critical elements to enable sustainable scale up of carbon removals.

**European Climate Law (ECL)**

Published in July 2021, as part of the European Green Deal, the ECL sets 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 Law 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.[75] The text also states that the EU shall aim to achieve a higher volume of removals in 2030, in line with the objective of achieving climate neutrality by 2050.[76] 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 (Carbon Removal Certification Framework, CRCF)**

The CRCF is for now a unique piece of policy globally. 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:

- Emission reductions from soils (including agricultural soils)
- Enhanced natural sinks (soils and forests)
- Carbon storage in products that lasts at least 35 years
- Permanent carbon removals that last at least multiple 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

[75] 'Regulation (EU) 2021/1119 of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999', *Official Journal* L243/1, 30 June 2021, Article 4(1) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119

[76] Regulation (EU) 2021/1119, Article 4(1)

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 when quantifying the 'net-benefit' of a project, potentially unambitious standardised baselines are to be used, and social sustainability safeguards have been left out of the framework. Most importantly, it barely scratches the surface in determining what the various units generated by certified activities are to be used for. It aims to solely certify these activities, leaving the use of units to potential future regulation and voluntary carbon markets. 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 - but double counting between the EUs 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 needed to operationalise it will follow in Delegated Acts (DAs), to be prepared by the European Commission in the coming years. These DAs will cover a broad set of issues, including the setting up of a CRCF registry, but crucially, the specific methodologies project developers must adhere to (i.e. how to quantify the net-benefits of their projects, address liability for potential reversals and measure and tackle sustainability impacts etc.).

**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 EU-level absolute target for net removals of 310 Mt of $CO_2$ equivalent, commencing 2026 until 2030.[77] As well as the absolute targets, relative national targets were 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.[78] 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".[79]

[77] 'Regulation (EU) 2023/839 Of The European Parliament And Of The Council Of 19 April 2023 amending Regulation (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out the targets of the Member States for 2030, and Regulation (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review', *Official Journal* L107/1, 19 April 2023, Article 4(2) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R0839

[78] CAN Europe, 'Mind the GAP! Assessing Climate Action under the 'Fit For 55' Package', May 2023 https://caneurope.org/content/uploads/2023/05/Assessment-climate-files-FF55.docx-2.pdf

[79] ' Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU' *Official Journal,* L156/1 Regulation, Article 3(1) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0841&from=EN

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).[80] 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 another example, 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.

While the NRL was adopted by the European Parliament with 329 votes in favour, 275 against and 24 abstentions,[81] at the time of writing, the vote in the Council has been postponed indefinitely with certain

[80] Cristina Urrutia et al., '2030 climate target plan: review of Land Use, Land Use Change and Forestry (LULUCF) Regulation', June 2021, p.19, https://www.europarl.europa.eu/RegData/etudes/STUD/2021/662929/IPOL_STU(2021)662929_EN.pdf

[81] EP press release, 'Nature restoration: Parliament adopts law to restore 20% of EU's land and sea', February 2024, https://www.europarl.europa.eu/news/en/press-room/20240223IPR18078/nature-restoration-parliament-adopts-law-to-restore-20-of-eu-s-land-and-sea

countries planning to vote against the law, potentially risking the required qualified majority of 55 percent of EU countries representing 65 percent of the bloc's population.[82] It therefore remains unclear whether the law will indeed pass.

**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 (EAFRD), 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.

Following recent, widespread farmer protests across the EU, the very basic conditionality criteria, along with the procedure regarding the national strategic plans risk being rolled back. The Commission has proposed introducing flexibilities to several GAECs, leading to voluntary schemes compensating for obligations going beyond the new GAEC baselines.[83] However, member states may also introduce temporary derogations to the GAECs in extreme cases of adverse weather conditions preventing farmers to properly work and comply with these requirements.[84] Additionally, farms under 10 hectares are relieved from controls and penalties

[82] Zia Weise and Louise Guillot, 'How the EU's flagship nature law became an electoral punching bag', Politico, March 2024, https://www.politico.eu/article/nature-restauration-law-european-parliament-election/
[83] EC Press Corner, 'Memo on the Commission's package of support to EU farmers', 15 March 2024 https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_1494
[84] EC Press Corner, 'Memo on the Commission's package of support to EU farmers'

related to compliance with the GAECs.[85] The overall aim of the proposal is to reduce the administrative burden for EU farmers and to grant national administrations increased flexibility in applying certain standards. As to the strategic plans, the Commission proposes to double the number of requests for amendment allowed for each Member State per calendar year.[86] While, at the time of writing, the proposal has been endorsed by the Agriculture and Fisheries Council configuration Council, the European Parliament must still adopt its position in plenary.[87] It remains to be seen what final modifications are brought to the Law.

Since its inception, the CAP has funded highly 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.[88] 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.[89] Eco-scheme uptake has also failed to meet expectations[90] and studies[91] indicate that the CAP Strategic Plans lack clear targets, measures, and funding to halt biodiversity loss and cut GHG emissions. Direct payments continue to be disbursed as untargeted farmer income, with conditionality standards being defined very loosely. 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, chiefly among them, farm income support and concerns about competitiveness in the international market.[92]

**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 fill-up 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

[85] EC Press Corner, 'Memo on the Commission's package of support to EU farmers'

[86] EC Press Corner, 'Memo on the Commission's package of support to EU farmers'

[87] Council of the European Union, 'Support for farmers: Council endorses targeted review of the Common Agricultural Policy', 26 March 2024, https://www.consilium.europa.eu/en/press/press-releases/2024/03/26/support-for-farmers-council-endorses-targeted-review-of-the-common-agricultural-policy/

[88] EEB, 'Agriculture' https://eeb.org/work-areas/agriculture/

[89] European Court of Auditors, 'Special Report Common Agricultural Policy and Climate: Half of EU climate spending but farm emissions are not decreasing', 2021, p.3, https://www.eca.europa.eu/Lists/ECADocuments/SR21_16/SR_CAP-and-Climate_EN.pdf

[90] Julia Dahm, "EU green farming schemes fall flat in Germany after meagre farmer uptake", Euractiv, June 2023, https://www.euractiv.com/section/agriculture-food/news/eu-eco-schemes-not-a-hit-among-farmers-german-ministry-data-shows/

[91] EEB and BirdLife International, 'Policy Briefing: CAP Strategic Plans - are they likely to deliver on given promises?', February 2022, https://www.birdlife.org/wp-content/uploads/2022/02/CAP-national-Strategic-Plans-Assessment.pdf; AgriCaptureCO2, 'Promoting carbon farming through the CAP', September 2023 https://eeb.org/wp-content/uploads/2023/09/Policy-Brief_Role-of-the-CAP-in-promoting-carbon-farming.pdf; ÖIR GmbH et al., 'Research for AGRI Committee: Comparative analysis of the CAP Strategic Plans and their effective contribution to the achievement of the EU objectives', 15 June 2023, https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2023)747255

[92] Alan Matthews, 'What is actually happening with agricultural incomes?' Cap Reform, February 2024, http://capreform.eu/what-is-actually-happening-with-agricultural-incomes/; Morgan Ody and Vincent Delobel, 'Farmers' protests in Europe and the deadend of neoliberalism', *Al Jazeera,* February 2024, https://www.aljazeera.com/opinions/2024/2/25/farmers-protests-in-europe-and-the-deadend-of-neoliberalism

policymaking and implementation, including up-to-date information on natural disturbances and forest disasters. 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 to have all soils 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.

## 2 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.

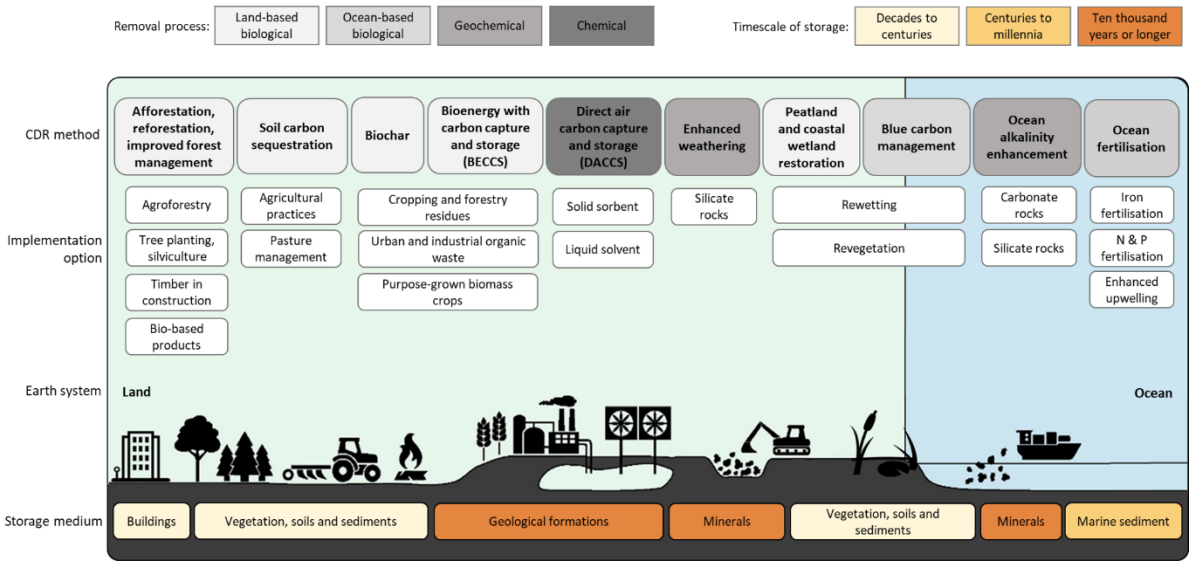



*Figure 11 Overview of carbon removal approaches, processes, and carbon storage types for a range of NETPs. Source: IPCC AR6 WGIII Chapter 12, Box 8, Fig. 1*

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 and 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[93] (see also "Modelling"), including at the EU member state level.[94]

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 above but focus on those most intensely studied within the NEGEM project. Technical performance indicators are provided at the top of each factsheet and along with other performance indicators (economic, environmental, resource security, social and governance) and

[93]Constanze Werner et al., 'Global Assessment of NETP Impacts Utilising Concepts of Biosphere Integrity', https://www.negemproject.eu/wp-content/uploads/2023/08/NEGEM_D3.3_Global-assessment-of-NETP-impacts-utilising-concepts-of-biosphere-integrity.pdf; Johanna Braun et al., 'Global NETP Biogeochemical Potential and Impact Analysis Constrained by Interacting Planetary Boundaries', https://www.negemproject.eu/wp-content/uploads/2023/05/D-3.2-Global-NETP-biogeochemical-potential.pdf; Antti Lehtilä et al., 'Quantitative Assessments of NEGEM Scenarios with TIMES-VTT', 31 October 2023, https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D8.2_NEGEM-scenarios.pdf; Piera Patrizio et al., 'Extended MONET-EU', 28 October 2021, https://www.negemproject.eu/wp-content/uploads/2022/04/D7.2-extended-MONET-EU.pdf

[94] Nixon Sunny, Solene Chiquier, and Niall MacDowell, 'Member State Specific Pathway for NETP Deployment', 31 May 2023, https://www.negemproject.eu/wp-content/uploads/2023/10/NEGEM_D4.5_Member-State-specific-pathway-for-NETP-deployment.pdf

information on the factsheets, have been determined using existing literature, such as the State of CDR report[95], and through expert consultations within the NEGEM consortium.

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.

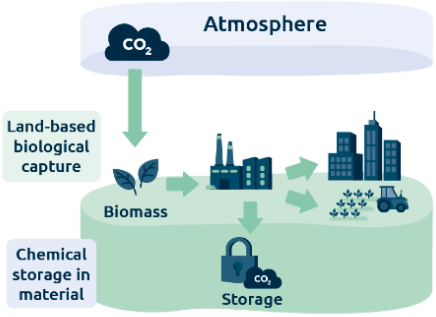
[95] S MSteve Smith et al., 'The State of Carbon Dioxide Removal - 1st Edition', https://doi.org/10.17605/OSF.IO/W3B4Zlast modified 8 August 2023, https://doi.org/10.17605/OSF.IO/W3B4Z

## 2.1 Biochar

# Biochar

NEGEM

*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 $N_2O$ 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 $CO_2e$).

Relevant regulatory frameworks: Regulation on an EU certification for carbon removals; 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**
Biochar properties (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.

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

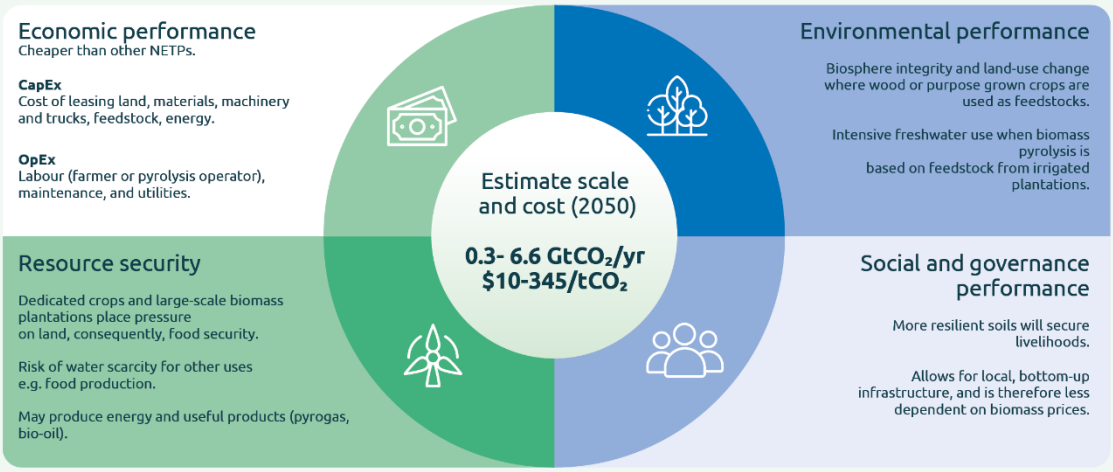
**HARD TO MONITOR**
Permanence of carbon storage biochar and reactivity in open field applications is still unproven. Applied over a large area it is difficult to monitor the dispersed storage of extracted $CO_2$ and adhere to MRV requirements with certainty.

**ECOSYSTEM DEPENDENT CO-BENEFITS**
Agricultural benefits are dependent on the soil and properties of the biochar, 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.

NEGEM

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




## 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).

Interaction between biochar and soil properties at the application site and the influence 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.

## Policy 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.

## Relevant literature

CDR Primer

European Biochar Market Report 2023/2024

State of CDR

NEGEM Deliverables NEGEM Deliverables: D1.2, D3.2, D3.8, D3.10, D4.5, D6.3, D7.2

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Funded by the European Union

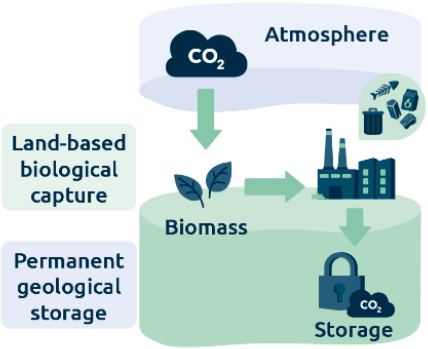
This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869192.

## 2.2 Biomass use with carbon capture and storage (BioCCS)

# Biomass with Carbon Capture and Storage

NEGEM

*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) |

## 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 emitted upon harvest (accounted for under LULUCF emissions accounting). Any biogenic $CO_2$ captured from biomass conversion in a BioCCS plant is then automatically considered a negative emission. Existing point source biogenic $CO_2$ emissions (e.g. pulp and paper) can also be captured.

There are currently 19 bioenergy production facilities around the world either in operation, piloting or under construction. Some leading 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 (see D5.4) followed by permanent geological storage.

Relevant regulatory frameworks: Biomass feedstock sourcing should comply with EU Renewable Energy Directive 2018/2001 (L328/82) guidelines for sustainable biomass.

### 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.

### CHALLENGES

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

**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.

**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.

**LONG CARBON PAYBACK TIMES**
Carbon debt payback time can be long depending on biomass source.

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

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

NEGEM

# 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 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 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.

BioCCS is perceived unfavourably 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 as a technology due to the lack of a standardised methodology. Clarity is needed on feedstock value chain carbon accounting as uncertainty exists as to whether they create net-negative emissions.

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

## Policy recommendations

Ensure that certification schemes provide appropriate incentives to securely capture of all concentrated $CO_2$ streams regardless of carbon emission type (fossil, biogenic); apply carbon accounting 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.

## Relevant literature

- Cobo et al. 2023
- EU Directive for use of energy from renewable resources
- Heck et al. 2018
- NEGEM Deliverables

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Funded by the European Union

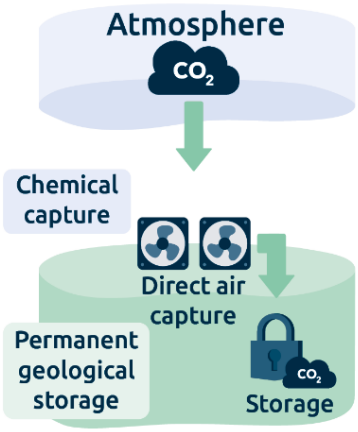
This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869192.

## 2.3 Direct Air Carbon Capture and Storage (DACCS)

# Direct Air Capture with Carbon Storage

NEGEM

*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 and accuracy of MRV | high |
| Key co-benefits | none |

## What is direct air capture with carbon storage 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 (ORCA) is on the scale of 4000 tons of $CO_2$ each year.

Relevant regulatory framework:
Geological storage is currently regulated under the EU CCS Directive (2009/31/EC). According to the IEA, potential cross-boundary $CO_2$ transport may be regulated under the London Protocol, once ratified, or by other options that align with applicable international law.

### ADVANTAGES

**PERMANENT STORAGE**
Sequested carbon is stored permanently with low risk of reversal.

**TRL**
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

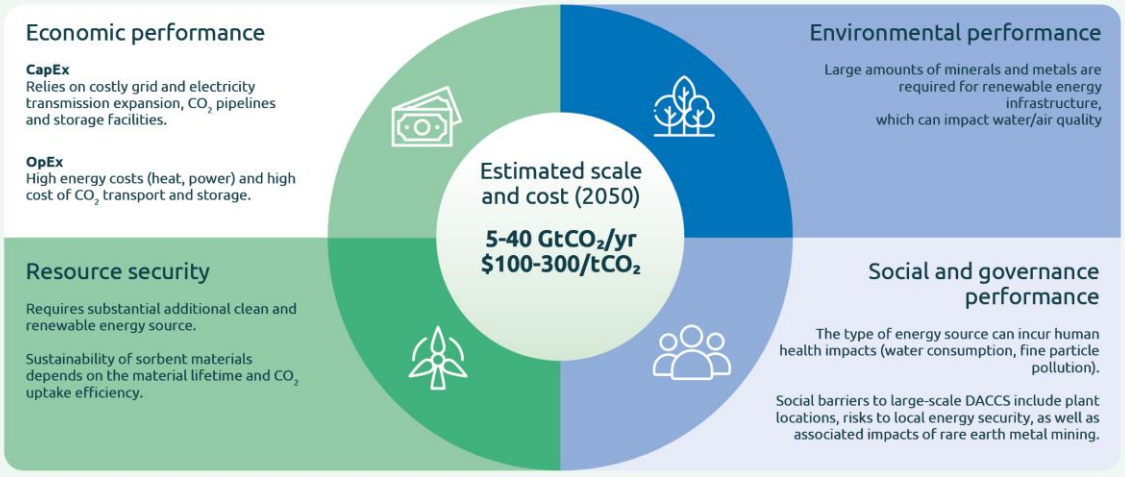
**ENERGY INTENSIVE**
Dependent on plentiful (and renewable) energy and heat source. Approximately 200mk² of non-arable land is needed for renewable energy generation to remove 1 Gt of $CO_2$.

**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.

**COST**
Costs are high and infrastructure is expensive to build.

**FEW CO-BENEFITS**
DACCS has fewer associated co-benefits compared to land-based sequestration.

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




## 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/tech 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.

## Policy 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.

## Relevant literature

Cobo et al. 2022

OECD/IEA report "Carbon Capture and Storage and the London Protocol" 2011

NEGEM Deliverables: D1.5, D2.1, D3.8, D3.9, D4.5, D5.2, D5.4, D6.3, D7.2, D8.2

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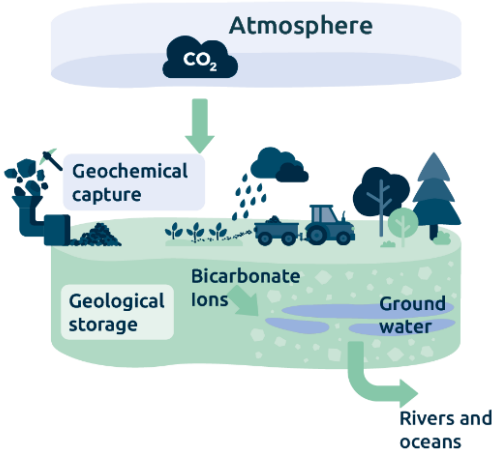
This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869192.

## 2.4 *Enhanced Weathering*

# Terrestrial enhanced weathering

NEGEM

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




| | |
|---|---|
| Expected permanence | millenia |
| Reversal risk | low |
| Uncertainty in amount of initially captured carbon | high |
| Uncertainty in amount of carbon stored over time | high |
| Ease and accuracy 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, e.g., on 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 (D8.1). 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 EFFECTIVE APPLICATION**
Comparatively cost-effective application, with large theoretical and indefinitely sustained capacity.

### CHALLENGES

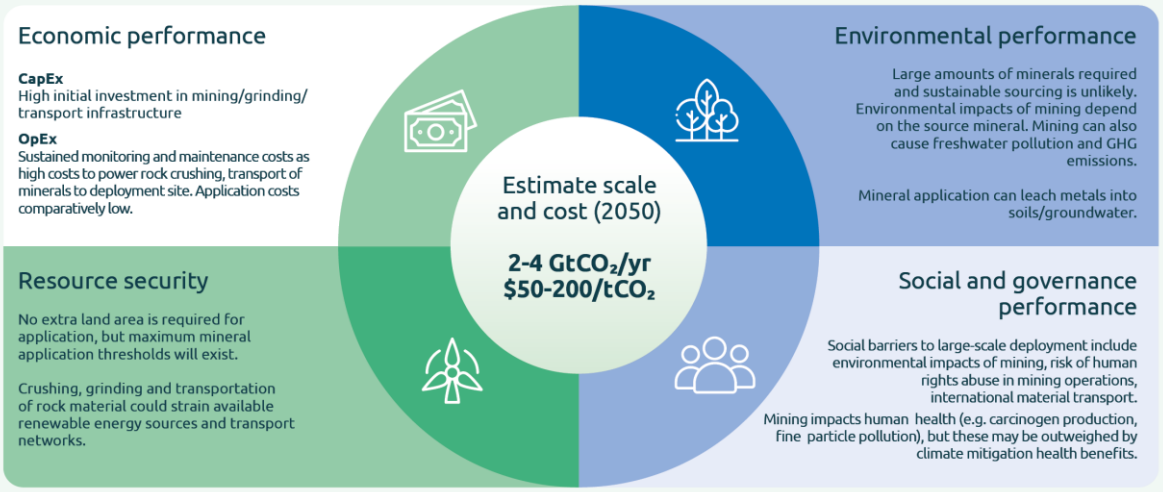
**HIGH VALUE CHAIN GHG EMISSIONS**
Both the rock crushing process and associated mining of minerals have high upfront GHG emissions.

**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.

**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.

**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.

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




## 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.

## Policy 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.

## Relevant literature

IPCC Information note: removal activities under the Article 6.4 mechanism

NEGEM Deliverables: D1.5, D2.1, D3.8, D3.9, D4.5, D5.2, D5.4, D6.3, D7.2, D8.2

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Funded by the European Union

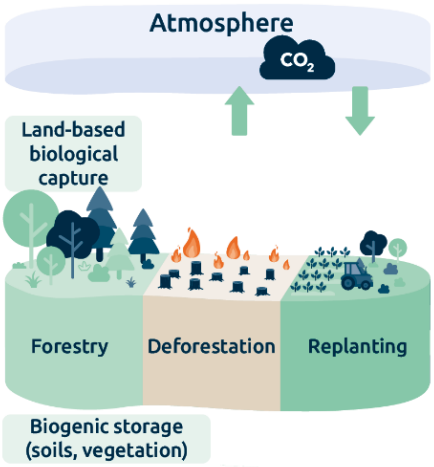
This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 869192.

*2.5 Reforestation and Afforestation*

# Afforestation and Reforestation

NEGEM

*A practice which enhances natural carbon stores and can reduce emissions*




| | |
|---|---|
| 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: EU 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**
Afforestation and reforestation already occur and is cheaper to implement than other NETPs. Little additional infrastructure is required.

**POSITIVE PUBLIC PERCEPTION**
Generally afforestation and reforestation are perceived well 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 capacity to sequester carbon and bears the 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.

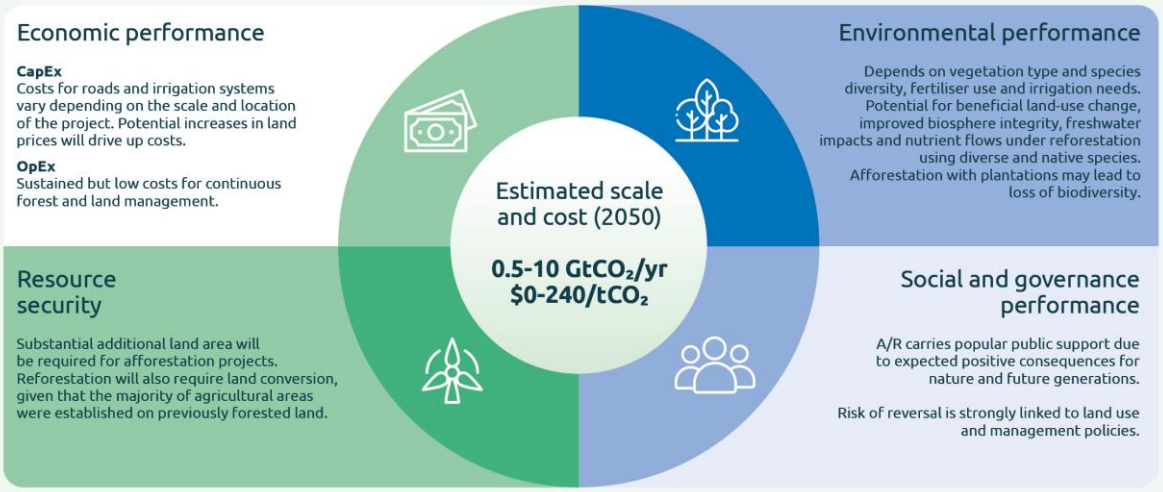
**LOCAL COMMUNITY RIGHTS**
Projects may not always prioritise the rights of local and marginalised communities, which are often excluded from decision-making processes.

**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.

NEGEM

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




## 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-carbon dioxide 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.

## Policy 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.

## Relevant literature

The Land Gap Report, update 2023

IPCC Special Report on Climate Change and Land, 2019

NEGEM Deliverables: D1.2, D2.2, D3.2, D3.3, D3.6, D3.7, D3.8, D3.10, D4.5, D5.5, D7.2

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Funded by the European Union

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*2.6 Soil Carbon Sequestration*

# Soil carbon sequestration

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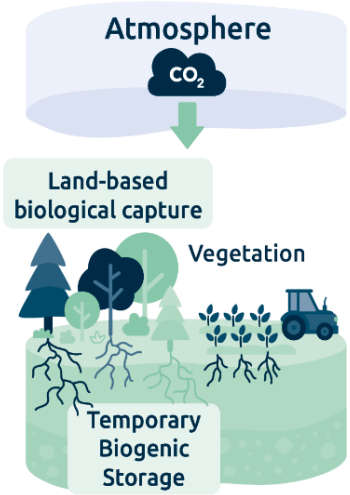
*A practice which enhances a natural process to store $CO_2$ and can reduce emissions*




| | |
|---|---|
| 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 contribute to ecosystem integrity |

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

Soil organic carbon (SOC) sequestration occurs because plants capture atmospheric $CO_2$ by 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 (e.g. 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, Regulation on an EU certification for carbon removals

### 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

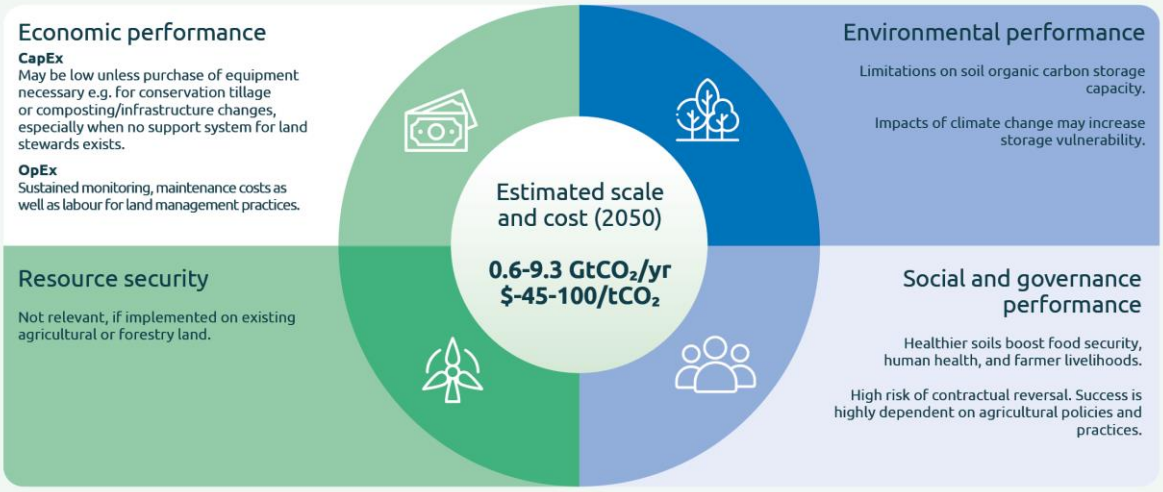
**RISK OF STORAGE REVERSAL**
SOC storage is vulnerable to disturbances that can reemit stored carbon.

**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.

**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.

# What is the sustainable potential of soil carbon sequestration?




## Current unknowns and future research perspectives

SOC content impacts soil function, and above a certain threshold, further increases ceases to 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.

## Policy 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, and 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.

## Relevant literature

- The Land Gap Report, update 2023
- IPCC Special Report on Climate Change and Land, 2019
- NEGEM Deliverables: D1.2, D2.2, D8.1

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Funded by the European Union

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# 3 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 lies in 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.[96] 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".[97] While afforestation generally presents are greater risk to the local ecology because of greater human intervention, reforestation is generally intended to restore an area's natural ecosystem to the original state. See also 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."[98] 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". Some CDR approaches, such as afforestation and reforestation, may unintentionally alter the Earth's albedo.

### *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, 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 processes that rely on biomass is the sustainable sourcing of 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 factsheet on "Biochar".

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

BECCS is a "negative emission 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

[96] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.542, https://doi.org/10.1017/9781009157940.008

[97] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.557, https://doi.org/10.1017/9781009157940.008

[98] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.542, https://doi.org/10.1017/9781009157940.008

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 ($CO_2$) 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.[99] 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 (1 $tCO_2e$) 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 (GWP). 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.[100] 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 the extraction of this GHG from the atmosphere and its permanent storage away from the atmosphere, either on land, underground or in the oceans. The following criteria need to be met for an activity to qualify as a removal[101]: (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".

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[99] Markus Hurskainen et al. 'Comprehensive sustainability assessment of Bio-CCS NETPs', 31 May 2021, https://www.negemproject.eu/wp-content/uploads/2021/06/NEGEM_D1.4.pdf

[100] Niclas Scott Bentsen, 'Carbon Debt and Payback Time – Lost in the Forest?', *Renewable and Sustainable Energy Reviews* 73 (June 2017): 1211–17, https://doi.org/10.1016/j.rser.2017.02.004

[101] Tanzer and Ramírez, 'When Are Negative Emissions Negative Emissions?'

### *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 fertilizers 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 with carbon capture and utilisation (CCU) or carbon capture and storage (CCS) respectively. CDR may result from these activities if the captured $CO_2$ is of atmospheric or biogenic origin, the $CO_2$ is permanently stored. The term 'carbon management' is, therefore, often used as a catch-all term for CCU, CCS and CDR. Use of this term risks obfuscating the important differences between these different activities, the most important being the very different climate impacts of these three types of activities. 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".[102] 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 the removal of these more technically difficult, because of the lower atmospheric concentrations. See also "Net zero".

### *Climate neutrality*

According to the IPCC[103], 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. The net impact on 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 law in the European Climate Law.

### *Co-benefits*

According to the IPCC[104], 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

[102] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.555, https://doi.org/10.1017/9781009157940.008
[103] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.545, https://doi.org/10.1017/9781009157940.008
[104] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.546, https://doi.org/10.1017/9781009157940.008

implementation practices, among other factors." To illustrate, BioCCS may generate both a negative emission and a valuable product, such as district heating or electricity. Further, when carefully implemented, certain land-based CDR approaches can bring about co-benefits for biodiversity, climate adaptation and food security. Concrete examples include increasing 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,[105] direct air carbon capture and storage (DACCS) refers to a "chemical process by which $CO_2$ is captured directly from the ambient air, with subsequent storage." See also factsheet on "Direct Air Carbon Capture and Storage (DACCS) ".

### *Enhanced Weathering*

Enhanced weathering entails "enhancing the removal of carbon dioxide ($CO_2$) 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", according to the IPCC.[106] See also 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 1 t of removals via different CDR approaches with varying characteristics. See also "The carbon cycle".

### *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 is 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".[107] Common techniques include (1) GHG removal, also known as "negative

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[105] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.547, https://doi.org/10.1017/9781009157940.008

[106] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.548, https://doi.org/10.1017/9781009157940.008

[107] Phillip Williamson and Ralph Bodle, 'Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework', Technical Series No.84. Secretariat of the Convention on Biological Diversity, Montreal, (2016), pp. 158, https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf

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*

A GHG is a gas that absorbs 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. [108]

### *Hard-to-abate*

See "Residual emissions".

### *Industrial carbon removals*

Industrial carbon removals rely on 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.[109] Importantly, the captured carbon must be stored permanently and align with the four principles for carbon dioxide removals.[110] These approaches frequently entail high costs and energy requirements (e.g. DACCS) or strong needs for natural resources (e.g. BioCCS); thereby raising concerns around sustainability. Industrial carbon removals differ from approaches with non-permanent sequestration in biological stores such as in afforestation, reforestation, soil carbon sequestration.

### *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.[111] This change can involve transforming grasslands into croplands, for instance, or agricultural lands to forests in reforestation or afforestation.

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[108] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), 550-551, https://doi.org/10.1017/9781009157940.008

[109] EC, 'Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions: Towards an ambitious Industrial Carbon Management for the EU', COM(2024) 62 final, 6 February 2024, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024DC0062

[110] Tanzer and Ramírez, 'When Are Negative Emissions Negative Emissions?'

[111] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), 553, https://doi.org/10.1017/9781009157940.008

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. [112] 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, with 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. Leakage can also occur when a country or sector implements mitigation measures that shift emissions, direct or indirect, to a different country or sector.[113]

#### *Life cycle Assessment (LCA)*

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.[114] 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.[115] 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.[116]

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[112] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.558, https://doi.org/10.1017/9781009157940.008

[113] 'Technical Summary', in: *Climate Change 2022: Mitigation of Climate Change* (IPCC 2022), p.124, https://doi.org/10.1017/9781009157926.00

[114] See Tanzer and Ramírez, 'When Are Negative Emissions Negative Emissions?' and the analysis by Carbon Market Watch 'Respecting the laws of physics – Principles for carbon dioxide removal accounting', December 2021, https://carbonmarketwatch.org/wp-content/uploads/2021/12/Respecting-the-laws-of-physics-Dec2021.pdf

[115] See p.20 in the report by Carbon Market Watch 'Respecting the laws of physics – Principles for carbon dioxide removal accounting'

[116] Duncan P McLaren et al., 'Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions', *Frontiers in Climate* 1 (2019), https://doi.org/10.3389/fclim.2019.00004

### *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.[117] This is also referred to as "Carbon neutrality or "Climate neutrality". This involves a combination of deep emission reductions and technologies that physically remove carbon dioxide from the atmosphere and permanently store it.

### *Pathways*

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.[118]

### *Residual emissions*

Currently the concept of residual emissions is not 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 to the extent that $CO_2$ 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 on 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.[119]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-

[117] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.555, https://doi.org/10.1017/9781009157940.008

[118] See previous

[119] UNFCCC, 'Race to Zero, Race to Zero Lexicon' 2024, https://racetozero.unfccc.int/wp-content/uploads/2021/04/Race-to-Zero-Lexicon.pdf

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[120] 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.[121]

### *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.[122] 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.

### *Source*

According to the IPCC[123] a source is "(a)ny process or activity which releases a GHG, an aerosol or a precursor of a GHG into the atmosphere (UNFCCC Article 1.9 (UNFCCC, 1992))."

### *Sustainability*

Sustainability, defined by the IPCC[124] 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 projects progress. There are nine technology readiness levels. TRL 1 is the lowest ("basic principles observed and reported") and TRL 9 (system is successfully proven to work is the highest)".[125]

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[120] Augustin Prado and Niall MacDowell, 'The cost of permanent carbon dioxide removal', Joule 7 (2023), 700-712, https://doi.org/10.1016/j.joule.2023.03.006

[121] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p.558, https://doi.org/10.1017/9781009157940.008

[122] See previous

[123] 'Annex VII: Glossary' in Climate Change 2021: The Physical Science Basis (IPCC, 2021), p. 2250 https://doi.org/10.1017/9781009157896.022

[124] 'Annex I: Glossary', in *Global Warming of 1.5°C* (Cambridge University Press, 2022), p. 558, doi: https://doi.org/10.1017/9781009157940.008

[125] https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

### *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)".[126] 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.[127]

[126] 'Annex II: Glossary' in Climate Change 2022: Impacts, Adaptation and Vulnerability (IPCC, 2022), p. 2925, https://doi.org/10.1017/9781009325844.029

[127] IPCC, 'FAQ Chapter 5', https://www.ipcc.ch/sr15/faq/faq-chapter-5/

For preparing this report, the following deliverables have been taken into consideration:

| D# | Deliverable title | Lead Beneficiary | Type | Dissemination level | Due date (in MM) |
|---|---|---|---|---|---|
| D1.2 | Comprehensive sustainability assessment of terrestrial biodiversity NETPs | ETH | Report | Public | 12 |
| D1.5 | Comprehensive sustainability assessment of geoengineering and other NETPs | Imperial | Report | Public | 24 |
| D2.1 | Quantitative survey of commercialisation mechanisms, as a report and review publication | UOXF | Report | Public | 17 |
| D2.2 | Interactions and trade-offs between nature based and engineered climate change solutions | UOXF | Report | Public | 24 |
| D3.2 | Report on global NETP biogeochemical potential and impact analysis constrained by interacting planetary boundaries | PIK | Report | Public | 24 |
| D3.3 | Report on global NETP assessment of impacts utilising concepts of biosphere integrity | PIK | Report | Public | 36 |
| D3.6 | Report on case study on impacts of largescale re-/afforestation on ecosystem services in Nordic regions | NIVA | Report | Public | 24 |
| D3.7 | Report on global impacts of NETP potentials on food security and Freshwater availability, scenario analysis of options and management choices | PIK | Report | Public | 36 |
| D3.8 | Report on comparative life cycle sustainability assessment of NETPs for impacts on human health, ecological functions and resources | ETH | Report | Public | 24 |
| D3.9 | Report on assessment of selected impacts on key non-renewable resource chains, case study on global demand, supply and trade-offs for metals and minerals in mitigation pathways | VTT | Report | Public | 24 |
| D3.10 | Report on synoptic assessment of global theoretical NETP potentials | PIK | Report | Public | 36 |
| D4.5 | Member State specific pathway for NETP deployment | Imperial | Report | Public | 36 |
| D5.2 | Stakeholder views on the business case for NETPs | UCAM | Report | Public | 24 |
| D5.4 | Final report on expert elicitation for NETPs | UCAM | Report | Public | 36 |

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|---|---|---|---|---|---|
| D5.5 | Public awareness and assessments of NETPs: Results of a series of cross-national public surveys | RUG | Report | Public | 42 |
| D6.1 | Publication “How do NETPs fit in existing climate frameworks?” | CMW | Report | Public | 36 |
| D6.2 | Publication “Principles for carbon negative accounting” | CMW | Report | Public | 18 |
| D6.3 | Publication “Global governance of NETPs - global supply chains and coherent accounting” | BELLONA | Report | Public | 30 |
| D6.5 | Publication “Who should use NETPs?” | BELLONA | Report | Public | 42 |
| D7.2 | Extended MONET-EU | Imperial | Other | Confidential | 17 |
| D7.4 | Value of intra-member state collaboration | Imperial | Report | Public | 36 |
| D8.2 | Quantitative assessments of NEGEM scenarios with TIMES-VTT | VTT | Report | Public | 38 |
| D8.3 | Final NEGEM medium-to-long-term vision | VTT | Report | Public | 44 |
| D8.7 | Updated NEGEM vision | VTT | Report | Public | 30 |