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C-SINK

ACTIONS REQUIRED TO SECURE THE LARGE-SCALE DEPLOYMENT OF THE LEADING CDR APPROACHES TO MEET EU CLIMATE TARGETS

D6.6 Training material report

Grant agreement no. 101080377

HORIZON-CL5-2022-D1-01-two-stage

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1. Information Sheet

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O	Other	

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2. Deliverable 6.6 – Training material report

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Reviewers	Laura Quijano, María José Márques (ISMC)
Date	17 March 2026

Deliverable description (as in the Grant Agreement)

D6.6 Training material report (ICA, M34) is linked to T6.5
T6.5 Development of learning resources: the objective of this task is aligned with Task 6.1 for public outreach but with a focus on training material with technical information on Carbon Dioxide Removal (CDR) approaches. ICAMCyL supported by ISMC and CS will produce online learning resources at different levels, such as simple factsheets on CDR technologies but also high-level training materials for engineers, PhD students and professionals. Partners will participate in interviews answering technical questions to produce the training materials that will be supplemented with scientific reports, outcomes and recordings from C-SINK workshops and other Events and available resources. The academic partners will support on this task by quality check and validation as well as using and disseminating the training material.

Abstract

This deliverable includes the description of 14 learning materials in the framework of Task 6.5. This deliverable by compiling relevant information of the six CDR technologies (BECCS, biochar, artificial soil, afforestation, microbiological CO_2 fixation, and enhanced rock weathering) evaluated in the framework of the C-SINK project that were communicated in a factsheet format for dissemination purposes.

The factsheets have been designed and produced with two different technical languages: one to reach a broad audience oriented to increase the public acceptability and comprehension of the CDR approaches; and the other for specialized and more technical target audience. Moreover, this deliverable describes the methodology followed to develop the factsheets to accomplish task completion.

C-SINK technical partners' support and contributions were crucial throughout the factsheet creation process, including their participation in content reviewing, approval, and dissemination. The factsheets content was based on the main outputs of the deliverables, relevant information provided by experts during the organized technical workshops, and specialized seminars information linked to Task 2.1 of the C-SINK project.

Keywords: CDR-T, CDR SOLUTIONS, LEARNING RESOURCES, INCREASING PUBLIC ACCEPTABILITY.

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3. List of figures, tables, and glossary

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Glossary

AF	Afforestation	EU	European Union
AS	Artificial soil	ERW	Enhanced rock weathering
BC	Biochar	GHG	Greenhouse gases
BECCS	Bioenergy with carbon capture and storage	HWP	Harvested Wood Products
CCP	Critical control point	KPI	Key performance indicator
CCS	Carbon capture, and storage	MCO_2	Microbiological CO_2 fixation
CCU	Carbon capture, and utilisation	MRV	Monitoring, Reporting, and Verification
CDR	Carbon dioxide removal	SIC	Soil Inorganic Carbon
CDR-T	Carbon dioxide removal technology	SOC	Soil Organic Carbon
CDW	Construction and demolition waste	TIC	Total Inorganic Carbon
CHP	Combined heat and power	TOC	Total Organic Carbon
D	Deliverable	TRL	Technology Readiness Levels
EBI	European Biochar Industry Consortium	WP	Work package
EC	European Commission		

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4. Executive Summary

The following training material report of the Carbon Dioxide Removal (CDR) approaches has been elaborated within the framework of the C-SINK project, which has received funding from the European Union's Framework Programme for Research and Innovation Action Horizon 2022 under Grant Agreement No 101080377.

The C-SINK project aims to establish the foundations upon which to build a standardized and transparent European CDR market with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

To adapt to current trends, technologies, necessities, and requirements, C-SINK assesses the viability (technological, legal, political, social, economic, and environmental) of a range of emerging and existing nature-based and engineered CDR methods. Their synergies in different combinations, for increasing the scale of CDR and its long-term storage, as well as what needs to be done to enable and ensure their rapid and large-scale will be addressed.

C-SINK has an interdisciplinary consortium made up of technological, carbon dioxide (CO_2) footprint accounting, legal, social, techno-economic, and environmental partners, as well as for dissemination, communication, and exploitation activities. In this regard, the C-SINK consortium is made up of 24 organisations from 11 different European countries which 15 are industries and SMEs, 2 industry-driven clusters and foundations, 3 Research Centres, and 4 Universities.

The overall goal of this deliverable is to encompass training materials with technical information on CDR approaches. It comprises learning resources on CDR technologies at two technical language levels, ranging from a specialized designed for engineers, PhD candidates, and industry professionals and other focused on the public in general.

Section 5 will provide the framework within which these materials are elaborated, the objectives, targeted audience, level of technical language.

A structured and sequential methodology was followed to create the contents of the factsheets is described in the sixth section together with the format.

Section 7 outlines the impact of these materials may have at both targeted audiences: public audience and technical / expert readers.

Section 8 lists the general conclusions.

Section 9 includes the list of references used for consultation and preparation of training materials.

Finally, a list of appendices from A to N attached to illustrate the training materials produced. The appendices from A to G and appendices from H to N correspond to technical / expert and public audience, respectively.

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5. Introduction

Within task 6.5, learning resources were designed to increase knowledge and comprehension, consequently, the social acceptability of different CDR technologies or solutions.

The factsheet format was selected for its versatility in conveying the message in a concise, easy-to-understand, and didactic way. In addition to providing in depth information about each CDR technology, the training resources also enable the particular and precise dissemination of the C-SINK project's results such as pilot projects or case studies developed and/or studied within the framework of the project. The target audience is classified as advocates (according to the GA classification). Finally, training resources are embedded to the project website, which in turn improve the impact and broad dissemination via the social media platforms.

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5.1. Target Audience

The target audience for learning resources is classified as Advocates, as shown in red in Table *1*

Table 1 C-SINK Target Groups with key messages, tools and expected outcomes

Target group	Key message	E & D & C	Expected outcome
Key players: those directly concerned, with an economic interest and power to influence and contribute to introduction of the innovative solutions developed into global markets. **Objective:** to upscale the CDR technologies in EU, including the adoption of MRV standards, demonstrate the project's advantages and economic benefit.			
End-users of the CDR technologies (early adopters and followers, emitters and land owners)	The uptake of CDR technologies developed by C-SINK will contribute to **a more resilient, environmentally friendly land management and** industry with new circular economy **business models** and **commercialisation strategies.**	E: C-SINK workshops and the "CO_2 Removal Helix". D: Scientific publications; Technology benchmarks; scientific conferences, meetings and fair trades; C-SINK final event. C: Project website; newsletters; mainstream and specialised media (Op-eds, guest commentaries and press releases); social media.	Adoption and incorporation of the CDR technologies with their corresponding methodology for assessment of their implications, and associated commercialisation strategies. New business and job generated related to CDR.
Technology providers for CDR	C-SINK is developing **trustable accounting** methodologies based on robust MRV standards and policy strategy built on comprehensive **scientific assessment** of different CDR approaches, potential carbon uptake and impacts over time.		Industrial partners having a viable market for these new technologies, in a manner that incorporates the new standards developed. New business and job generated related to CDR.
Public and private investors aiming to start new CDR business	Investments to CDR technologies developed by C-SINK will contribute to a more resilient, environmentally friendly industry with **new circular economy business models**.		Secured investment conditions and framework to enable CDR as a sustainable business; New business and job generated related to CDR.
Context Setters: they have the power to change structures, standards, policies, regulations and framework conditions. Engaging with them is key to achieve long-term impact of the project outcomes. **Objective:** to establish the standardisation and methodologies to the management of CDR technologies and to ensure supportive policy framework.			
Policy makers at international levels (i.e. EIT Energy; DG CLIMA, Renewable Energy Directive)	A supportive **policy framework** is needed to scale up and **standardize CDR technologies and accounting** methodologies and advance the achievement of the EU climate goals and obligations under the Paris Agreement.	E: Engagement in C-SINK workshops and the "CO_2 Removal Helix". C-SINK Clustering activities; D: Policy briefs; technology benchmarks; scientific conferences, meetings and fair trades; C-SINK final event.	Ensured supportive policies, regulations, standards, and framework for CDR technologies and their accounting methodologies.
Standardisation organisations (VCS, CEN)	C- SINK is developing trustable **accounting** methodologies based **on robust MRV standards** and policy strategy built on comprehensive scientific assessment of different CDR		Established standards for application of the CDR technologies, and the associated accounting methodologies.

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	approaches, potential carbon uptake and impacts over time.	C: Project website; newsletters; mainstream and specialised media (Op-eds, guest commentaries and press releases); social media.	
Professional networks and platforms (i.e. IPCC, IRENA EURAMET)	A **supportive policy** framework to scale up CDR technologies and advance the achievement **of EU climate goals and obligations** under the Paris Agreement.		Support focused on the proliferation of CDR technologies, favourable policy conditions and broader acceptance of the technologies.
Relevant **EU projects** and other related initiatives	C-SINK is developing a multidisciplinary network/ecosystem (helix) to facilitate the **exchange of ideas and expertise** regarding the **CDR technologies**.		Increased exchange of ideas and expertise on enhancing the CDR technologies; further collaboration beyond the project.
Advocates: they don't have a direct economic interest in the project outcomes but are highly relevant in the social, educational and academic context. Their endorsement means public support and reputation and the build-up of social and knowledge structures. **Objective:** Scientific exchange of ideas on CDR; capacity building; training students and academics on different CDR options; Show innovations developed at the project and increasing awareness and knowledge of CDR technologies.			
Scientific-technical community (academics, researchers, PhD students)	C-SINK is conducting comprehensive **scientific assessment** of different CDR approaches, **potential carbon uptake and impacts over time** to develop **trustable accounting.**	D: Scientific publications; conferences; C-SINK final event; Webinars, factsheets on CDR technologies; learning resources; C: Website; newsletters; mainstream and specialised media (Op-eds, guest commentaries and press releases); social media;	Enhanced research, innovation and development on enhance performance of the CDR technologies.
NGOs, CSOs	CDR technologies will help to advance the **achievement** of the **EU climate goals** and obligations under the **Paris Agreement**.		Better lobbying opportunities, increased awareness and knowledge of CDR technologies;
Concerned citizens	C-SINK will conduct comprehensive scientific assessment of different CDR approaches to **increase general knowledge about CDR technologies**.		Enhanced knowledge and awareness of CDR technologies and increased social acceptance.

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5.2. Objective and Added Value

To develop learning materials for technical experts, including engineers and PhD students, postdocs and related professionals such as environmental engineers, climate scientists, policy analysts, and specialized researchers involved in environmental, legal, scientific, and social aspects related to CDR technologies. Through a clear and defined structure, facilitate access to and knowledge of CDR, the CDR technologies used in the C-SINK project and the project's own objectives and, through this knowledge, increase its acceptability among both specialists and the public.

5.3. Levels

The factsheets are divided into two technical language levels. Level 1 is aimed at a technical/expert audience and consists of training materials for engineers, PhD students, and postdocs and related professionals within the CDR methods such as environmental engineers, climate scientists, policy analysts, and specialized researchers focused on CDR technological. This level uses a more specialized and technical language to present each CDR approach, and illustrate the description with process diagrams, characterization, parameterization, and information based on technology-specific deliverables (D2.2-D2.9) and two more cross-cutting deliverables (D2.1 and D2.10). The second technical language level was designed and created for a more public general audience and uses a more accessible language. In this level, the text content was reduced, and didactic materials such as graphics and photographs were used to facilitate the understanding of the content and grasp the essence of each CDR technology.

5.4. Technologies

Factsheets were designed and released for six CDR technologies, which were thoroughly evaluated by the C-SINK consortium in terms of their potential for carbon removal, permanence, environmental and social impacts, and large-scale potential:

- Microbiological CO_2 fixation (MCO_2)
- Afforestation (AF)
- Biochar (BC)
- Artificial soils (AS)
- Bioenergy with Carbon Capture and Storage (BECCS)
- Enhanced Rock Weathering (ERW)

Furthermore, two more factsheets were designed and released to expose and inform about the potential synergies between these six technologies and how their interaction could improve the effectiveness of carbon removal and fixation capacity of ecosystems / materials and its viability and feasibility through a combined use.

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6. Methodology

6.1. Setting up learning resources within the C-SINK project

Firstly, for the proper execution of the task, the period to perform the task was divided into three main blocks, as shown in Figure 1. To divide this period, it was considered the deadlines for deliverables, the technical workshops, webinars, and seminars conducted by the technical partners and experts in each of the CDR technologies.

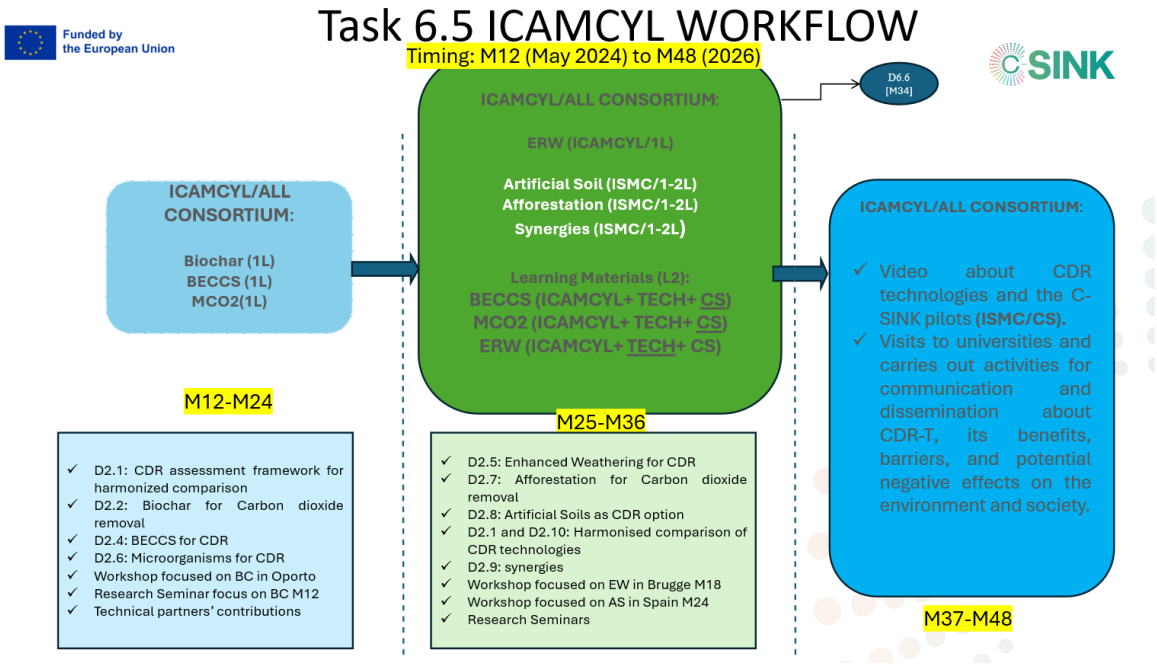


Figure 1. Planned Task 6.5 workflow

Secondly, once the deliverables were planned, each factsheet was created considering the CDR technology and language level as described above. To ensure a harmonised structure, a template was shared among the technical experts of each technology within C-SINK partners. This structure, besides a common layout, stablished the following sections depending on the targeted public:

Technical/ expert audience

- Title
- Short introduction
  An overview of the necessity for CDR, the framework of politics and agreements around this issue and the C-SINK objectives.
- Key facts / general info on CDR
  CDR definition and associated technologies.
- Explanation and/or context of the technology
  Definition of the addressed technology, permanence,
- Current state of the technology as CRD
  To date production, capacity and costs of the addressed technology.
- Impacts or implications
  The positive and negative effects and co-effects and detected risks associated to each approach.
- Impacts or implications of the C-SINK project
  How C-SINK project falls into the CDR technology reality and the importance MRV pre-standards and policy strategies.
- References

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A list of the references used with the format of the Publication Manual of the American Psychological Association, Seventh Edition (APA 7th).

- Contact information
  A direct link to the C-SINK website

General public

- Title
- Short introduction
  A paragraph addressing the necessity for CDR, the framework of politics and agreements around this issue and the C-SINK objectives.
- How does the technology work?
  A description of the scientific procedure of the technology.
- How much carbon can store?
  An overview of technology capacity to CDR
- Other co-benefits and/or risks
  An explanation of how this technology affects the reader daily life.
- Brief explanation of C-SINK Project
  The importance of MRV pre-standards and policy strategies and how are they being addressed in the project.
- References
  A list of the references used with the format of the Publication Manual of the American Psychological Association, Seventh Edition (APA 7th).
- Contact information
  A direct link to the C-SINK website

Even though the structure was flexible since each technology has a different develop status and its own idiosyncrasy, all the above-mentioned topics were addressed on each factsheet. Furthermore, technology-specific and audience-adapted graphs and photographs were created to contextualise and facilitate the understanding of the factsheets.

Once the draft factsheet was completed, it was shared with the technical partners and/or experts of the C-SINK consortium for quality content review and feedback. The partners and reviewers are listed in Table 2.

Table 2. Technologies and technical partners involved in the review and approval of learning materials.

Technology	Technical Partners
BC	UED, PYR, IMF
BECCS	CSIC, UED, FCO
MCO2	EKO
ERW	MEM, PAS, KUL, BOL
AS	UNIOVI, LURTEK
AF	FCO, CES
Synergies	ISMC, ALL

Finally, once the training materials were approved by the technical partners, they were shared with Climate Strategies (CS), the partner responsible for communication and dissemination, to create the final layout. Learning materials were delivered and disseminated through the C-SINK website and social media (https://c-sinkproject.eu/publications/learning-resources/) (Figure 2 and Figure 3).

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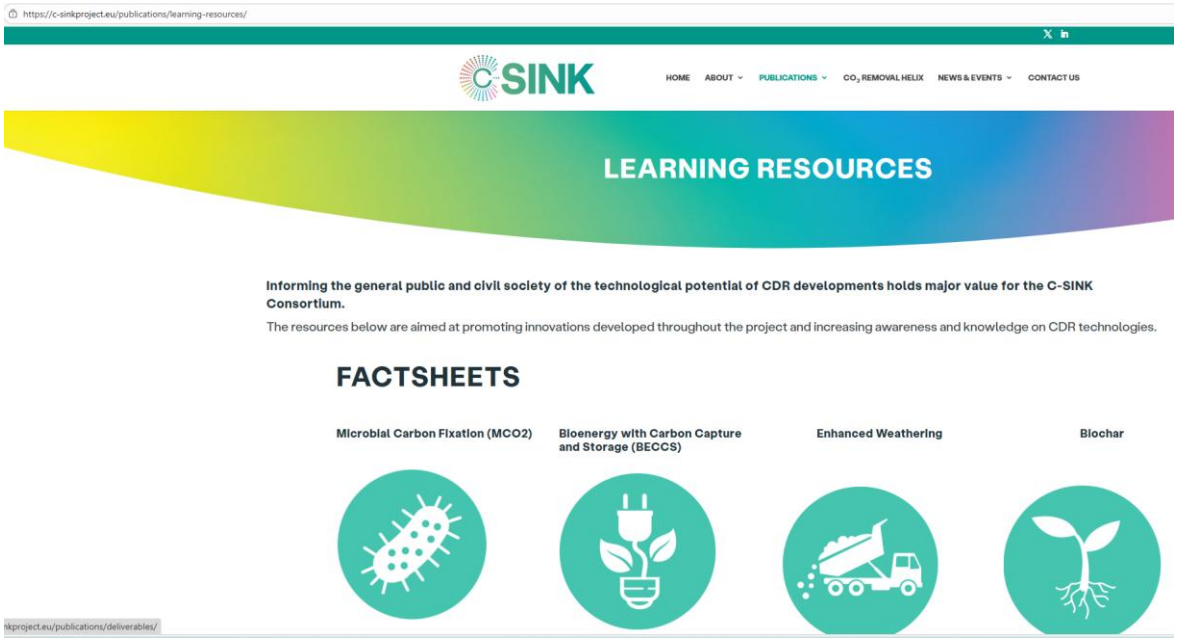


Figure 2. Learning materials were released on the C-SINK website.

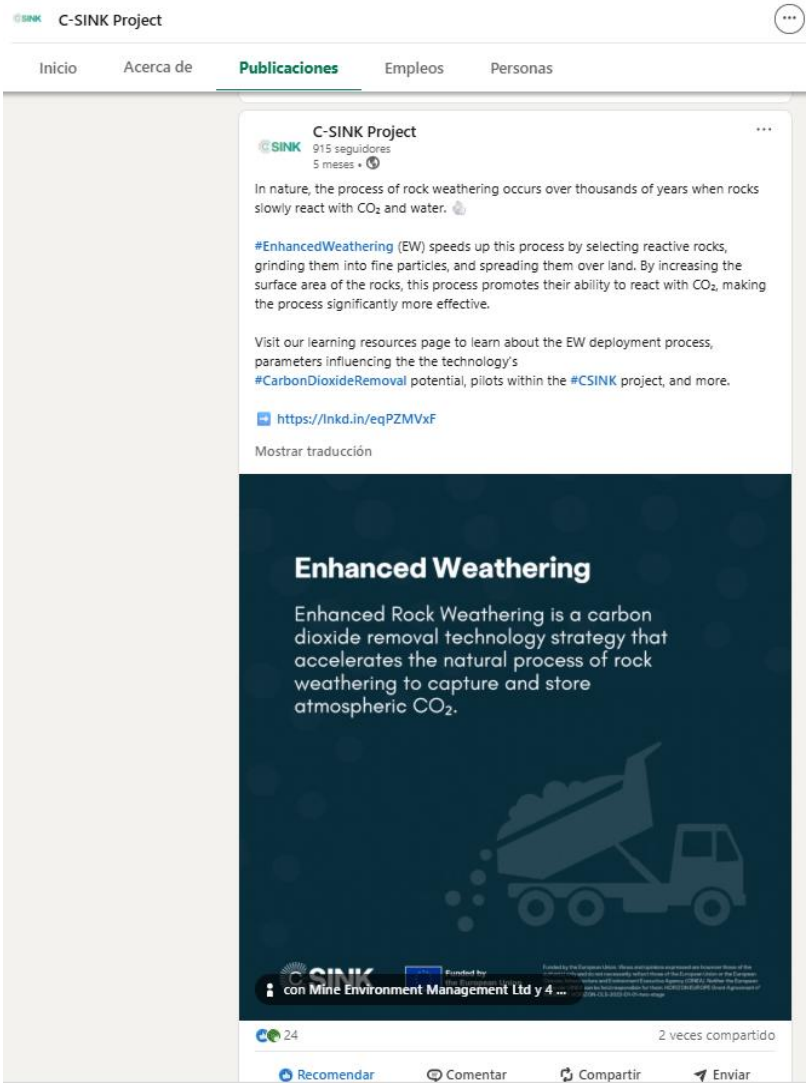


Figure 3. Learning materials were disseminated on the C-SINK LinkedIn account.

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6.2. Format

Factsheets on CDR technologies with public and technical / expert languages were designed using .doc or .docx as formats. These factsheets contain all the technical information but are adapted for the different levels (Table 3) of the Advocates Group (Table 1).

Table 3 Comparative Table: C-SINK Factsheets Level 1 vs. Level 2

Technology	Document Level	Language Type	Pages	Sections	Key Message	Target Audience
BECCS	Level 1	Technical and Academic	5	9	BECCS captures biogenic CO_2 from energy production for permanent geological storage.	Technical Experts
	Level 2	Comprehensive and Accessible	3	7	BECCS is a mature technology that provides durable carbon removals while generating energy.	Public and Policy Makers
ERW	Level 1	Technical and Academic	8	13	Enhanced rock weathering uses mineral dissolution of (ultra)mafic rocks to lock CO_2 in stable carbonate forms.	Technical Experts
	Level 2	Comprehensive and Accessible	3	8	Spreading crushed rocks on farmland or beaches captures CO_2 and improves soil fertility.	Land Managers and Public
MCO_2	Level 1	Technical and Academic	6	13	Microbial biostimulants accelerate natural soil biochemical pathways to store carbon as organic and inorganic matter.	Agronomists and Experts
	Level 2	Comprehensive and Accessible	2	7	Harnessing soil microorganisms allows agricultural lands to capture CO_2 while boosting crop health.	Farmers and Public
Biochar	Level 1	Technical and Academic	5	13	Pyrolysis converts biomass into stable biochar, moving carbon from the short-lived biosphere to the geosphere.	Technical Experts
	Level 2	Comprehensive and Accessible	4	9	Biochar is a highly competitive CDR method that locks carbon for centuries while improving soil quality.	Policy Makers, Farmers, and Public
Artificial Soils	Level 1	Technical and Academic	6	5	Engineered Technosols reuse waste to create functional sinks that accumulate both organic and inorganic carbon.	Technical Experts
	Level 2	Comprehensive and Accessible	5	5	Specially designed soils capture carbon while recycling waste materials to restore degraded land.	Local Authorities and Public
Synergies	Level 1	Technical and Academic	8	6	Co-deploying complementary technologies maximizes removal efficiency and mitigates the risks of individual methods.	Strategic Planners and Technical Experts
	Level 2	Comprehensive and Accessible	6	5	Combining different carbon removal approaches offers a	Decision Makers and Public

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					practical and resilient path to reach EU climate targets.	
Afforestation	Level 1	Technical and Academic	7	5	Sustainable forest management on non-forested land establishes long-term carbon sinks in biomass and soils.	Forestry and Technical Experts
	Level 2	Comprehensive and Accessible	7	5	Planting trees is a practical nature-based solution that removes CO_2 while restoring ecosystem services.	Landowners and Public

6.3. Versions and updates of the deliverable

No update is expected for D6.6. However, Task 6.5 is not being finished with the accomplishment of this deliverable since a didactic video about CDR technologies (produced by ISMC and CS) and trainings to selected Universities are aimed to boost the social acceptability and dissemination of the project and the completion of the task.

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7. Results

Six CDR technologies in two different technical languages levels in a factsheet format as learning / training materials were communicated and disseminated. Two more learning materials (one for each level 1 and 2) were created addressing the synergies between these six technologies. These are shown in Appendices A-N and Table 4.

Table 4 Factsheet summary

Factsheet	Technology	Level	Link to the website	Appendix
Microbial Carbon Fixation	MCO_2	1	https://c-sinkproject.eu/wp-content/uploads/2025/04/MCO2-Factsheet.pdf	Appendix A
Bioenergy with Carbon Capture and Storage	BECCS	1	https://c-sinkproject.eu/wp-content/uploads/2025/01/FS2_BECCS_CCU_final__.pdf	Appendix B10.1
Enhanced Rock Weathering	ERW	1	https://c-sinkproject.eu/wp-content/uploads/2025/04/FS3_ERW_Final.pdf	Appendix C
Biochar	BC	1	https://c-sinkproject.eu/wp-content/uploads/2025/11/FS4-BC-L1-3.pdf	Appendix D
Artificial Soils	AS	1	https://c-sinkproject.eu/wp-content/uploads/2026/02/CLEAN-FS6-AS-L1-ISMC.pdf	Appendix E
Afforestation	AF	1	https://c-sinkproject.eu/wp-content/uploads/2026/02/FS5-AF-L1-ISMC_.pdf	Appendix F
Synergies	Synergies	1	https://c-sinkproject.eu/wp-content/uploads/2026/02/CLEAN-FS7-SYNERGIES-L1-Final.pdf	Appendix G
Microbial Carbon Fixation	MCO_2	2	https://c-sinkproject.eu/wp-content/uploads/2026/01/MICROBIAL-CO2-FIXATION-MCO2-3.pdf	Appendix H
Bioenergy with Carbon Capture and Storage	BECCS	2	https://c-sinkproject.eu/wp-content/uploads/2026/01/BioEnergy-with-Carbon-Capture-and-Storage-BECCS-4.pdf	Appendix I
Enhanced Rock Weathering	ERW	2	https://c-sinkproject.eu/wp-content/uploads/2025/12/3-Enhanced-Rock-Weathering-ERW-1.pdf	Appendix J
Biochar	BC	2	https://c-sinkproject.eu/wp-content/uploads/2026/01/Biochar-Factsheet-Jan26.pdf	Appendix K
Artificial Soils	AS	2	https://c-sinkproject.eu/wp-content/uploads/2026/02/Factsheet-6-Artificial-Soils-AS.pdf	Appendix L
Afforestation	AF	2	https://c-sinkproject.eu/wp-content/uploads/2026/03/Afforestation-2702.pdf	Appendix M
Synergies	Synergies	2	https://c-sinkproject.eu/wp-content/uploads/2026/02/Synergies-Factsheet-Feb-2026-v2.pdf	Appendix N

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All materials are available on the C-SINK website, in which KPI9: “150 people using developed learning resources” was successfully completed. The C-SINK website section dedicated to learning materials currently shows 544 viewers and visitors, where learning resources are displayed. Additionally, 1,469 impressions were found on different posts on the C-SINK social media platforms. More details are summarized in Table 5.

Table 5. Metrics from the C-SINK website's learning resources page.

Parameter	Measurement
Views	544
Average engagement time	22s
Event count (basically any interaction with the page – i.e., clicks, scrolls)	1,469
File download times	170

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8. Conclusions

The core message across all factsheets is that reducing greenhouse gas emissions alone is insufficient to meet the Paris Agreement goals and reach EU climate neutrality by 2050. Consequently, CDR technologies, ranging from nature-based solutions like afforestation to engineered methods like BECCS, are a "climate necessity and strategic opportunity".

A critical sub-message is that no single technology can deliver the required removals alone; success depends on the strategic integration of complementary technologies in synergistic combinations to maximize efficiency and resilience.

From a general point of view, the conclusions that can be extracted from the current deliverable are:

- Six (BC, BECCS, MCO_2, AS, AF, and ERW) CDR-technologies were duly communicated and disseminated, completing part of Task 6.5 of the C-SINK project through factsheets format. However, for the completion of Task 6.5, a video based on this information and some university visits are still pending.
- 14 learning materials at two levels on the C-SINK website and social media, with the technical partner's support, were communicated and disseminated.
- Task 6.5 addressed and supported the CDR acceptance-increasing actions through learning resources, considering the information stated in D2.1-D2.10 deliverables, workshops held so far within the project, as well as seminars, webinars, among others.
- Task 6.6 is fully connected with Task 2.1, following the deliverables suggestions; therefore, Co-effects and social benefits were crucial for increasing/improving the social acceptance of CDR-T studied.
- KPI9 “150 people using developed learning resources” was successfully completed.

The factsheets are intended to have several direct impacts as communication and strategic tools, distinct from the broader operational goals of the C-SINK project. The direct impacts of the Factsheets are:

- To **raise awareness and increase the willingness** of specific groups, such as farmers and land managers, to adopt novel CDR technologies by clearly demonstrating their role and benefits.
- The factsheets are designed to outline the a**ctions required to secure the large-scale deployment** of leading CDR approaches. They serve as a practical guide for moving these technologies from experimental phases to meeting EU climate targets.
- **Serve as a source for educational simplification** by providing the public version of technical reports, the factsheets **explain and highlight** complex methods for a broader audience, clarifying "how it works", "how much it costs", and "how long it takes".
- The factsheets communicate the **MRV pre-standards** developed by the project intended to establish the "foundations for a standardized and transparent European CDR market" by providing stakeholders with trustworthy accounting methodologies.
- By presenting data on **costs, Technology Readiness Levels (TRL), and potential risks**, the documents act as a decision-support tool for policy makers and investors to evaluate the maturity and economic viability of different carbon removal paths.
- They provide a condensed format for **comprehensive scientific assessments** regarding CO_2 uptake potential and environmental safety, ensuring that research findings are accessible to those responsible for implementation

Furthermore, the factsheets encourage different actions depending on the reader's role:

- **For policy makers:**

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- **Establish stability:** Provide long-term, predictable policy and financial support for R&D and demonstration phases, as many CDR benefits take decades to manifest.
- **Integrate frameworks:** Formally include CDR and its synergies within land restoration, waste management, and energy policies.

❖ **For land managers and farmers:**

- **Adopt co-beneficial practices:** Implement methods like **microbial biostimulants** or **biochar** soil amendments, which offer immediate benefits and increased crop yields.
- **Diversify Income:** Explore new revenue streams through **carbon credits**.

❖ **For industry and investors:**

- **Build infrastructure:** Invest in the necessary **carbon capture and storage (CCS) infrastructure** hubs to lower per-tonne costs through economies of scale.
- **Industrial synergy:** Mining companies can adopt ecological processing pathways to increase the value and purity of mineral products while capturing carbon.

❖ **For the public:**

- **Increase awareness:** Follow the progress of the C-SINK project and its transparent monitoring efforts to build trust in CDR as a durable climate solution

Overall, the usage data of C-SINK learning materials reflects this content as a tool for Advocates interaction with the C-SINK project and the CDR technologies. The learning materials are serving to reach a relevant audience and engagement beyond simple page visits and, consequently, the factsheets have proof to be a positive indicator of user interest in accessing the resources more thoroughly.

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10. Appendix

10.1. Appendix A

MCO_2 - L1

Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 1
DELIVERED BY ICAMCYL & EKOLIVE

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): MICROBIAL CO_2 FIXATION (MCO_2)

INTRODUCTION

In the Paris Agreement (United Nations, 2015), the necessary bases were established to address the issue of climate change as urgent, using the highest level of technological and scientific knowledge to contain and address the problem on a global scale. Subsequently, the Intergovernmental Panel on Climate Change (IPCC) announced the results of a rigorous assessment based on scientific, technical, and socio-economic data available in the literature on global warming of 1.5°C and the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. Resulting model pathways with no or limited overshoot of 1.5°C indicate that emissions must decline by 45% to keep warming below 1.5ºC by 2030, and towards net zero by 2050 (IPCC, 2018b).

The C-SINK project funded by Horizon Europe aims to establish the foundations to build a standardized and transparent European CDR market with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

WHAT IS CARBON DIOXIDE REMOVAL (CDR)?

Following the IPCC's 8th Assessment Report, CDR refers to activities that remove carbon dioxide (CO_2) from the atmosphere and store it permanently (IPCC, 2018a). They can be grouped into nature-based and technology-based removals (Meyer-Ohlendorf, 2020). Nature-based enhancing biological sinks of CO_2 are, among others, afforestation (AF), reforestation (RF), and soil carbon sequestration (SCS) as a result of BCO_2. Technology-based removals employ chemical engineering to achieve long-term removal and storage. Among others, an example is bioenergy with carbon capture and storage (BECCS), but there are additional approaches including improving soil quality, enhanced weathering, and the production of biochar (Ornelas et al., 2023).

GLOSSARY

Aerobic metabolism: Type of metabolism which occurs in the presence of oxygen.

Anaerobic metabolism: Type of transformation produced with no presence of oxygen.

Autotrophic bacteria: Type of bacteria which synthesizes their own food. They derive energy from light, utilize simple inorganic compounds like CO_2, water, etc., and convert them into organic compounds to supplement their energy requirements.

Biological carbon fixation (BCO_2): A nature-based technology in which living organisms absorb and convert CO_2 into organic matter through biochemical pathways (Berg, 2011). Organic compounds created by BCO_2 are used to store energy and to build other biomolecules. Carbon is primarily fixed through photosynthesis, when sunlight is available, and chemosynthesis, in the absence of sunlight.

Heterotrophic microorganisms: Organisms that obtain their energy and carbon from organic compounds.

Microbial carbon fixation (MCO_2): A sub-term of BCO_2, refers to the fixation of CO_2 by microbes into usable organic substances by means of enzymatic reactions.

Soil microbiota: The abundance and diversity of microbes residing in the soil (bacteria, fungi, archaea, protists, and algae).

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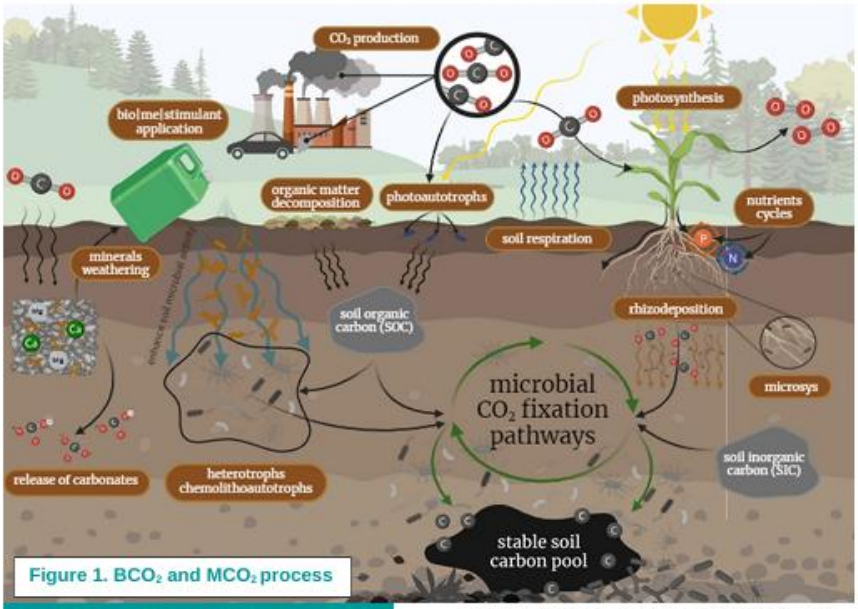


Figure 1. BCO_2 and MCO_2 process

DEFINING CO_2 REMOVAL FROM A MCO_2 STANDPOINT & PROCESS

CO_2 removal by BCO_2 refers to the amount of CO_2 that is consumed and stored by microorganisms in the soil and plants growing in a defined area. When plants photosynthesize, they take CO_2 from the atmosphere and convert it into organic matter, such as wood, leaves, and roots, while releasing oxygen (see Figure 1).

Apart from BCO_2 fixation by plants, MCO_2 occurs in all microorganisms, both autotrophic and heterotrophic. Biological carbon fixation by autotrophs can utilize light or inorganic chemical energy to fix atmospheric CO_2 through evolved carbon fixation pathways (Gong et al., 2018). Autotrophic bacteria synthesize all their constituent cells using CO_2 as a carbon source in that way (Ge et al., 2016).

Importantly, recent studies report significant biological CO_2 fixation by heterotrophic microorganisms. These microorganisms are capable of consuming CO_2 and incorporating it into their metabolism during bioremediation and biofertilization processes (Bräuer et al., 2016); (Chen et al., 2009); (Kimura et al., 2011); (Miltner et al., 2005); (Santoro et al., 2013).

WHAT IS THE CURRENT STATE OF THE TECHNOLOGY?

Various microorganism based biostimulants are commonly applied by farmers to increase yields – however, impact on CO_2 fixation in soil was never the main purpose of their use, consequently monitoring and verification of their impact are lacking.

The major unknowns in MCO_2 technology are the poorly understood related processes involved, the scalability, and the very limited data. There are no clear MRV standards or methodologies. It is very well known that carbon gets sequestered in soil as Soil Organic Carbon (SOC), but there is also a possibility of carbon sequestration in the form of Soil Inorganic Carbon (SIC). Moreover, there is a lack of understanding of biochemical pathways happening in soil microbiota. Furthermore, methodologies

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for the determination of carbon sequestered in soil are not uniform and standardized at the moment. SIC is not taken into account when calculating CO_2 stored in the form of soil carbon.

DEFINITION OF EACH PROCESS-STEP

1. Bioleaching or microbiological weathering for 5 days, in which bacteria multiply and produce metabolites dissolving minerals, to produce 2 types of biostimulants to be used as microbial soil activity enhancers: *ekofertile® plant* and *microfertile® plant – water consumption.*

2. Pumping of biostimulants to plastic canisters – *energy consumption by the pump.*

3. Printing the labels – *energy consumption.*

4. Transport of biostimulants to farmers – *fuel consumption.*

5. The farmer mixes biostimulants with water and applies the solution by spraying – *fuel consumption, water consumption*, or by irrigation system – *electricity and water consumption.*

6. Organic and inorganic carbon monitoring in soil.

7. Harvest and analysis of yield – harvest by tractors, transport to food factories – *fuel consumption*.

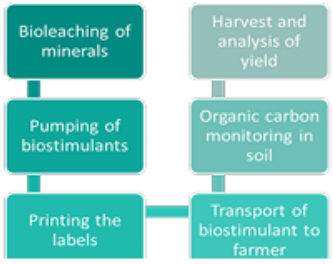


Figure 2. MCO2 step-process.

PERMANENCE

The most common timeframe applied in MCO_2 in the form of SCS is decades to centuries according to IPCC[1]. Regarding the time factor in removing CO_2, soil microbiota communities show significant roles in carbon removal from the atmosphere and fixing it in the soils. However, potential fluctuations during large-scale deployment regarding microbial communities have not been sufficiently studied. Carboxylase reactions are rather immediate reactions and result in the assimilation of CO_2 into organic metabolites by microorganisms. This CO_2 incorporation by chemo-organo-heterotrophic microorganisms has been referred to as "heterotrophic carbon dioxide assimilation" or "heterotrophic carbon dioxide fixation" and can be assumed to have an immediate effect (Braun et al., 2021).

REVERSAL RISK

MCO_2 produces SIC and SOC. Regarding SIC, MCO_2 presents a low risk. Sylvera[2] has ranked mineralized CO_2 (SIC) to have no practical risk of reversal. Microbial carbon fixation of SIC is proven in research done by Liu et al. (2020) where they demonstrated that desert soil microbes are directly involved in fixing atmospheric CO_2 via biomineralisation. Same is proven by Braun et al. (2021) for heterotrophic bacteria's ability to fixate CO_2. However, Sylvera considers that SOC has a high risk of reversal since there is a high range of factors that trigger carbon reversal — flooding, droughts, wildfires, disease, renovation of a pasture, change in soil acidity or change of the soil nutrient content (named "depletion event" in a guide[3] to the estimating sequestration of carbon in soil using default values method).

COSTS, TRL, AND TYPICAL SCALE

Some estimated costs are 1,09 € per litre of biostimulant and it is applied based on the type of crops in rates from 10–200

[1] https://www.ipcc.ch/report/ar6/wg3/downloads/outreach/IPCC_AR6_WGIII_Factsheet_CDR.pdf
[2] https://www.sylvera.com/blog/permanence-carbon-credits
[3] https://cer.gov.au/document/guide-to-estimating-sequestration-carbon-soil-using-default-values-method

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C-SINK Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

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litres per hectare. It is affordable for farmers because the cost return of this novel technology is 10 times higher compared to conventional products due to no diseases, yield increase, proteins increase, and possible reduction on N fertilizer up to 50%. The potential additional profits from carbon credits will be calculated during the field trials within the C-SINK project. Usually, it ranges from an additional 30–300 € per hectare.

TYPICAL SCALE OF CO_2 REMOVAL/LIMITING FACTORS

According to Shimmel (1987), dark fixation of CO_2 in agricultural soil, based on the rate of radiolabelled CO_2 incorporation, varied from 0.2 to 4.8 mg/m²h. Data from Šantrůčková et al. (2005) projected the rate of estimated heterotrophic CO_2 fixation which ranged from 36.5 mg CO_2/m²h, in the soil with pH 7.5, to 2.8 mg CO_2/m²h, in the soil with pH 4.8.

No industrial-scale data is available. Thereby a pilot is essential to study MCO_2 deployment capacity.

C-SINK experts have found that limiting factors to scaling MCO_2 include obtaining import permissions, local registrations, and sales for the biostimulants in the EU[4].

NEGATIVE EFFECTS

High water consumption.

CO-EFFECTS

Benefits for farmers: sugar and protein content increase, faster development of crops, disease resistance, drought resistance, yield and profit increase with low investment per hectare, increased efficiency of agrochemicals.

Benefit for mining companies: new ecological processing technology increases the value and purity of minerals.

The co-effects described above have been verified and measured[5], for instance, if the right dosage of the biostimulant is used. Also, the mentioned co-effects can potentially positively influence the use of biostimulants as MCO_2 CDR-T because farmers are primarily interested in applying it due to agricultural benefits and not specifically CO_2 sequestration potential.

The C-SINK project will allow demonstration of biostimulants' role in MCO_2 CDR-T which will further raise awareness and willingness of, not only farmers, but all land managers to apply this technology. This will enable carbon sequestration and contribute to the goals of the Paris Agreement in tackling climate change by supplementing existing CO_2 mitigation efforts.

MCO_2 PILOTS DEVELOPED WITHIN THE C-SINK PROJECT



Figure 3. C-SINK MCO_2 pilots

- Several case studies on farmland with and without crops will be conducted in three countries (Germany, Slovakia, and Croatia). The soil will be inoculated with

[4] In EU countries – in some cases it is a simple two-page declaration, and labels submitted to a relevant authority. In other countries no need for anything, it is automatically mutually recognized. E.g. in Spain, it is on a volunteer basis to prepare this declaration. Only in Switzerland registration is needed, while UK is free to sell without any action.

[5] It is possible to measure yield increase, protein increase etc. to calculate an increase.

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up to 1´000 microbial species of heterotrophic, autotrophic microorganisms and microalgae produced by bioleaching operations. The objective of case studies will be to evaluate the potential and mechanisms by which microorganisms contribute to soil carbon sequestration and retention. Each location is characterised by different climates and different soil types.

Field trials in Slovakia are conducted on raspberries and cereals, on red currants and blueberries in Germany and, in vineyards in Croatia.

Soil samples are taken periodically throughout the growing season to assess the soil sequestration potential. This is done according to ISO 18400-104:2018 Soil Quality – Sampling. Soil samples' collection and application of different concentrations of *ekofertile® plant* and *microfertile® plant* to raspberries by spraying and irrigation are shown in Figure 3. – results can be seen at the farm in Košické Oľšany. Furthermore, soil samples are analysed to obtain parameters of interest: total organic carbon, total inorganic carbon, humus, pH, total nitrogen, phosphorous, potassium, magnesium, copper, C/N ratio, and bulk density.

To process data and determine SCS, a variety of methodologies will be used to evaluate their correctness and suitability such as Microbial Carbon Mineralization (MCM) – Methodology for Quantification and Crediting of Carbon Dioxide Removal from Andes, VM0042 – Methodology for Improved Agricultural Land Management from Verra, Carbon Credits (Carbon Farming Initiative—Estimation of Soil Organic Carbon Sequestration using Measurement & Models) Methodology Determination 2021 from Australian Government & Soil Carbon Measurement Methodology from Carboneg.

Finally, the impact on biological carbon sequestration in the soil will be monitored and compared in sprayed and irrigated areas within the C-SINK project.

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10.2. Appendix B

BECCS - L1

Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 2 DELIVERED BY ICAMCYL & CSIC. REVIEWED BY UED AND FCO.

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): BIOENERGY with CARBON CAPTURE and STORAGE (BECCS)

INTRODUCTION

The Paris Agreement (United Nations, 2015), laid the groundwork for urgently addressing the issue of climate change, using the highest level of technological and scientific knowledge to tackle this global problem. Following this, the Intergovernmental Panel on Climate Change (IPCC) released the results of a thorough assessment based on scientific, technical, and socio-economic data available in the literature (IPCC, 2018a). The report compared a 1.5°C and 2°C increase above current pre-industrial levels, concluding that to curb warming to 1.5°C, emissions need to be cut by 45% by 2030 and net-zero emissions achieved by 2050.

The C-SINK project aims to establish the foundation for creating a standardized and transparent European carbon dioxide removal (CDR) market, with reliable accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

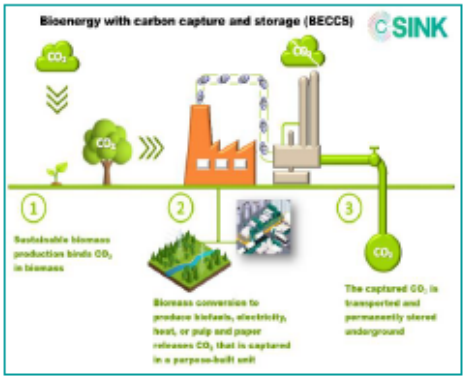


Figure 1. BECCS conceptual scheme

WHAT IS CARBON DIOXIDE REMOVAL (CDR)?

According to the IPCC (IPCC, 2018b) CDR stands for activities that remove CO_2 from the atmosphere and store it permanently. They can be grouped into nature-based and technology-based removals (Meyer-Ohlendorf, 2020). Nature-based solutions encompass reforestation (RF), afforestation (AF), enhanced weathering (EW), soil carbon sequestration (SCS), upgrading soil quality properties, and biochar production (Ornelas et al., 2023), while technology-based removals employing chemical engineering to reach long-term removal and storage, including DACCS (direct air carbon capture and storage), and BECCS (bioenergy with carbon capture and storage).

Bioenergy with carbon capture and storage (BECCS) involves capturing and permanently storing carbon dioxide (CO_2) produced when biomass—plant-based materials such as agricultural residues, forestry products, or dedicated energy crops—is burned or transformed into fuels to generate energy (Figure 1).

There are two principal BECCS pathways currently under development, in compliance with the International Energy Agency (IEA). The first uses biomass to produce biofuels (such as biodiesel or bioethanol), capturing the CO_2 that would otherwise be released during production. The second generates heat and electricity by combusting biomass and then captures the resulting CO_2 before it is released into the atmosphere.

Approximately 2 million tonnes of CO_2 from biomass are captured worldwide each year, mainly through bioethanol production. However, estimates suggest that 2–4 billion tonnes of CO_2 (gigatonnes) could be re-

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moved annually if BECCS is deployed sustainably, which is crucial for meeting international climate goals aimed at limiting global temperature rise to 2 °C (ICSC, 2023).

One key measure of BECCS's performance is its carbon efficiency, reflecting how much of the CO_2 initially fixed by the plants remains stored rather than returning to the atmosphere. Biomass-to-power systems typically remove more CO_2 per tonne of feedstock, whereas biofuel production delivers more energy from the same amount of biomass (Fajardy et al., 2019). In practice, real-world BECCS systems are expected to achieve removal efficiencies of around 65–85%, influenced by the capture process, transport logistics, and the overall supply chain.

Carbon capture and storage (CCS) refers to splitting CO_2 from large point sources, for instance, power stations, and afterward permanently storing it in geological formations (IPCC, 2018b). Carbon capture and utilisation (CCU), by contrast, involves using captured CO_2 in short-lived products such as carbonated drinks or greenhouse fertilisation, meaning most of this carbon ultimately returns to the atmosphere. Because of this short lifespan, CCU is generally not considered a form of carbon dioxide removal (CDR).

CDR specifically refers to approaches that draw CO_2 out of the atmosphere for the long term; some CDR methods, such as direct air capture and BECCS, may use the same infrastructure as CCS but differ in that they actively reduce existing atmospheric CO_2. As a result, provided that biomass resources are sustainably managed, capture rates remain high, and associated supply chains minimise additional emissions, BECCS can play a crucial role in tackling climate change.

DEFINING CO_2 REMOVAL FROM A BECCS STANDPOINT

The potential for carbon sequestration with BECCS is measured based on the amount of carbon in the biomass used as a feedstock. When calculating the net carbon removal of BECCS, we need to consider the CO_2 emissions generated throughout the entire BECCS process: from biomass cultivation, harvesting, processing, and conversion, to the efficiency of the carbon capture plant, emissions from transportation, injection, storage, as well as any indirect CO_2 emissions or leakages within the entire BECCS system.

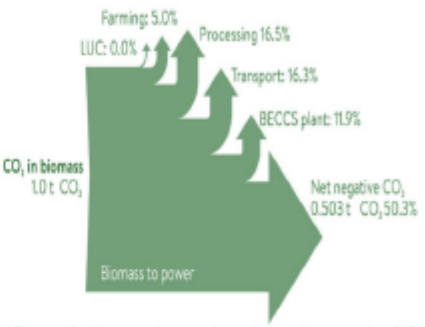


Figure 2. Illustrative carbon flow diagram for BECC
Source: (Fajardy et al., 2019).

BECCS VALUE CHAIN

There are inherent differences in the biomass conversion process, therefore, the rate of atmospheric CO2 removed per unit of feedstock switches from one method to another. Understanding the challenges and opportunities of each BECCS route is therefore vital for determining its overall contribution to decarbonising the economy and achieving climate targets.

The BECCS value chain comprises four main stages: biomass production, biomass processing and transport, biomass conversion to energy, and capture, and transport storage of the biogenic CO_2 emitted upon biomass conversion (Fajardy, 2022).

1. Biomass feedstock: refers to either the primary product, such as dedicated energy crops or harvested wood from forestry, or a by-product, such as forestry residues, agricultural residues, municipal solid wastes, waste wood from industries, or manure, of an activity. These different feedstocks vary in cost, energy intensity,

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Study	Method	Country	Biomass feedstock	Conversion technology	Capture technology	Cost (2022 US$)[a]	
						US $/MWh	US$/t CO_2 [b]
Bui et al. [16]	LCC[c]	UK	Waste wood, forest and crop residues	Combustion	Post-combustion using MEA[d]/ MDEA[e]	–	165-204
Rhodes and Keith [32]	TEA[f]	UK	Wood chips	Combustion and gasification	Pre-, post- and oxy-combustion	209-388	253-319 (100-158)
Pour et al. [17]	Not specified	Australia	MSW, biomass and LFG[g]	Combustion and gasification	Post-combustion using MEA[d]	174-251	129-246
Lu et al. [33]	Not specified	China	Wheat straw	Gasification	Post-combustion using MEA[d]	108	–
Yang et al. [34]	LCC[c]	China	Straw	Combustion	Post-combustion using MEA[d]	169	159 (59)
Rhodes and Keith [32]	Not specified	US	Not specified	Gasification	Post-combustion using glycol/membrane	69-140	(42-55)
Negri et al. [35]	LCC[c]	Europe	Energy crops	Combustion	Post-combustion using MEA[d]	191-277	160-225
Al-Qayim et al. [36]	LCC[c]	UK	White wood pellets	Combustion	Post-combustion using ecoamine	317-354	104-206 (109-111)
Cheng et al. [37]	Not specified	US	Crop and woody residues, and biosolids	Hydrothermal treatment, gasification and combustion	Post-combustion	–	00-314
Hollenstein et al. [38]	Not specified	Sweden	Woody biomass	Pulp mill (integrated)	Absorption (Selexol process)	–	(40-79)

[a] All costs are converted to the 2022 US$ from the original costs and currency using the EPPI-Centre Cost Converter [37].
[b] The cost ranges not in brackets are the total cost of BECCS per t CO_2 removed, while those in brackets are the cost of CO_2 capture only.
[c] LCC: Life cycle costing.
[d] MEA: Monoethanolamine.
[e] MDEA: Methyldiethanolamine.
[f] TEA: Techno-economic assessment.
[g] MSW: Municipal solid waste; LFG: Landfill gas.

Table 1. Summary of cost studies of bioenergy with carbon capture and storage. Source: (Saharudin et al., 2023b).

greenhouse gas emissions, and environmental impacts, meaning the choice of feedstock can substantially affect the sustainability and economics of the entire BECCS system.

2. Biomass processing and transport: biomass often requires treatment or densification to meet the quality and format requirements for the chosen conversion pathway. This processing can incur additional energy use and emissions, but can also reduce transport costs, especially for denser forms of biomass. Deciding how much to process biomass before transport involves balancing higher upfront costs against potentially lower logistical expenses.

3. The third stage, biomass conversion, includes a range of processes such as power generation, hydrogen production, biodiesel, and bioethanol, as well as various industrial applications. These pathways differ by their energy efficiencies, carbon capture efficiencies, and overall costs. Some technologies also produce co-products with potential economic value, which may offset part of the operational expenditure.

4. Capture, transport, and geological storage: CCS can be utilized in various conversion pathways using different technologies. These include post-combustion (for example, capturing CO_2 from exhaust gases in air-fired biomass combustion), oxy-combustion (burning biomass in pure oxygen), or pre-combustion capture (as in biomass gasification). Each technology has its own cost profile and level of technical complexity. The captured CO_2 is compressed, transported by pipeline or ship, and then injected into suitable geological reservoirs, where it can be permanently stored. As shown in Table 1, the associated costs and overall feasibility of large-scale deployment will depend on factors like regional infrastructure, storage availability, and regulatory frameworks.

WHAT IS THE STATE OF THE ART OF BECCS?

BECCS is often described as a mature technology because all the technical components for capturing and storing CO_2 from biomass-based processes already exist. According to the Global CCS Institute (GCCSI, 2023), there are currently two operational BECCS facilities in the United States: Archer Daniels Midland (ADM)

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Illinois Industrial, which produces ethanol and has a theoretical capture capacity of 1 million tonnes per annum (Mtpa), and Red Trail Energy Richardton Ethanol, with a capacity of 0.18 Mtpa. Although more than 40 advanced BECCS developments are registered in North America, ADM's Illinois facility remains the only large-scale BECCS plant in operation there.

In Europe, two facilities are under construction: the Hafslund Oslo Celsio Waste-to-Energy Plant in Norway and the Shell Energy and Chemicals Park Rotterdam in the Netherlands. Each is designed to capture around 0.4 Mtpa of CO_2 and is expected to become operational in 2024. Denmark's Amager Bakke Waste-to-Energy facility, with a planned capacity of 0.5 Mtpa, is slated to begin operations in 2025. Leading European projects include Drax in the United Kingdom and Stockholm Exergi in Sweden. Drax aims to capture 8 Mt of CO_2 each year by 2027 and eventually become carbon-negative by 2030, with a long-term ambition of delivering 16 Mtpa of negative emissions. Stockholm Exergi plans to capture and permanently store 0.8 Mt of CO_2 per year by 2027. In both cases, the captured CO_2 will be transported and stored in geological formations beneath the North Sea.

In Spain, the Bioeléctrica de Garray biomass power station is notable for being the first biomass plant connected to the national grid as a regulated source of electricity. Approved by Red Eléctrica Española (Spain's electrical system operator), this facility generates approximately 100,000 MWh annually, avoiding around 24,100 tonnes of CO_2 emissions and supplying electricity to 27,000 homes. The plant uses an automated biomass silo and can incorporate olive-oil solid waste into its fuel mix. Beyond electricity generation, it features a carbon capture and utilisation (CCU) system that sends captured CO_2 to a nearby greenhouse, improving plant growth. Future plans also include producing fertilisers from biomass ash, demonstrating the broader socioeconomic benefits that BECCS developments can bring to rural regions such as Soria.

BECCS DEPLOYMENT: COST & TRL

The successful implementation of BECCS depends greatly on having sufficient carbon capture and storage (CCS) infrastructure. Although first-of-a-kind CCS facilities have helped reduce associated costs, limited investor confidence remains the key barrier to large-scale commercial deployment. One of the primary concerns is the medium-term financial risk of integrating the full CCS chain, which increases capital expenditure for new projects. In addition to minimising investment risk, there are opportunities to lower costs by aggregating CO_2 sources and exploiting economies of scale for CO_2 transport and storage.

The cost of implementing BECCS varies considerably due to differences in underlying capture and storage processes. According to various estimates, the cost of avoiding one tonne of CO_2 spans from about US$15 to US$400, depending on the industrial or energy sector (Global CCS Institute, 2019; Samaniego et al., 2023). Research by Fajardy et al. (2021) suggests that the overall economic costs and the required carbon prices for meeting stabilisation targets of 1.5–2 °C in the second half of this century can be significantly reduced by leveraging existing technology. This study also indicates that BECCS could serve as a form of technological "safety net" at carbon prices of around US$240 per tonne of CO_2. Table 1 presents a literature review of BECCS costs based on different conversion and capture configurations (Saharudin et al., 2023), while Figure 3 summarises the Technology Readiness Levels (TRLs) across the BECCS value chain for various feedstocks, processes, and products.

Looking at the longer-term potential for CO_2 removal, the IPCC has estimated that BECCS could remove a total of between 1

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FEEDSTOCK	TRL	PROCESS	TRL	PRODUCT	TRL
Lignocellulose (Forestry and Wood)	Large-scale Pilot to Full-Commercial	Combustion	Full Commercial	Steam/Heat	Full Commercial
Agricultural residues	Large-scale Pilot to Full Commercial	Gasification	Basic Concept to First-of-Kind Commercial	Ethanol	Full Commercial
Sugars/starch crops	Proof-of-concept Reached to Full Commercial	Fermentation	Prototype Pilot to Full Commercial	Biodiesel	Full Commercial
Organic waste	Full Commercial	Anaerobic digestion	Full Commercial	Liquid hydrocarbon	Concept Validation to Pre-commercial Demonstration
Algae	Pre-commercial Demonstration	Extraction	Pre-commercial Demonstration to Full Commercial	Methane	Full Commercial
Oil crops/waste	Proof-of-concept Reached to Full Commercial	Densification	Full Commercial	Vegetable oil	Full Commercial
		Pyrolysis	Large-scale Pilot to Full Commercial	Pellets	Full Commercial
				Biochar/Charcoal	Full Commercial

Figure 3. Summary of TRLs for BECCS technology depending on feedstocks, processes, and products. Source: Global CCS Institute, 2019.

and 85 gigatonnes of CO_2 by 2050, highlighting the uncertainty in future deployment scenarios. By contrast, Fuss et al. (2018) project a narrower range of 0.5 to 2 gigatonnes of CO_2 removal per year by 2050. Although these figures differ considerably, both indicate that BECCS could become a pivotal option for climate mitigation if scaled up under supportive policy and market conditions.

CONS OF BECCS

Despite its promise, BECCS faces considerable uncertainties regarding its long-term potential, environmental impacts, cost viability, and broader socio-economic implications. Nevertheless, if managed responsibly, BECCS may play a key role in simultaneously delivering energy and negative emissions (Geden & Schenuit, 2020).

- Limited Scope Without Trade-Offs BECCS alone is unlikely to deliver the scale of negative emissions needed if deployed without considering competing land uses and the pressures placed on agricultural systems. Research indicates that large-scale expansion of biomass crops could contribute to higher food prices, deforestation, and ecosystem degradation if not carefully managed.
- Perceived Risks and Public Acceptance Risks such as "mitigation deterrence" (the fear that negative-emission technologies might reduce incentives for emission cuts), land-use conflicts, and the potential for intensified deforestation underscore the social and environmental concerns surrounding BECCS. These issues may affect public acceptance and policy support, slowing adoption.

PROS OF BECCS

- Compatibility with Existing Bioenergy Industry: As existing bioenergy facilities can be retrofitted with CO_2 capture technologies, BECCS offers a relatively direct way to scale up carbon removal within an established industrial framework. This compatibility helps lower certain barriers to entry—particularly for companies already investing in bioenergy.
- No Fundamental Scientific Barriers: According to various assessments, including IPCC reports, there are no unsolvable scientific or technical hurdles preventing net CO_2 removal via BECCS. The core challenge lies in economic and policy implementation rather than in fundamental technology gaps.
- Sustainable Replacement of Fossil Fuels: When sourced responsibly, biomass can serve as a renewable feedstock, reducing dependency on fossil fuels while contributing to stable energy access. However, ensuring the sustainability of feedstock production is critical for maintaining genuine climate benefits.
- Economies of Scale in CO_2 Transport and Storage: BECCS can be clustered with other industries requiring CCS, allowing shared pipelines and storage sites. Such infrastructure "hubs" reduce per-tonne costs by

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spreading expenses across multiple projects, improving the overall economic feasibility of CCS.

In summary, if the environmental and socio-economic challenges associated with biomass production are effectively managed—and if sufficient financing, policy support, and infrastructure are established—BECCS may provide a valuable pathway for achieving negative emissions (Geden & Schenuit, 2020). Although it is not a standalone solution, many experts view BECCS as a key component in a wider portfolio of climate mitigation options needed to reach net-zero targets.

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10.3.Appendix C

ERW - L1

Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 3 DELIVERED BY ICAMCYL, KUL, MEM, PAS & BOL.

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): Enhanced Rock Weathering (ERW)

INTRODUCTION

Carbon dioxide (CO_2) is regarded as the primary greenhouse gas (GHG) responsible for climate change, with atmospheric concentrations having risen by 50% compared to pre-industrial levels due to human activities, notably fossil fuel burning and deforestation (Smith et al., 2024). While efforts are underway to reduce GHG emissions by transitioning to renewable energy sources, these actions alone are insufficient to meet the Paris Agreement goals (UNFCCC, 2015). Hence, the development of carbon dioxide removal (CDR) methods, also known as negative emission technologies (NET), is imperative. These technologies enable the removal of current and previously accumulated CO_2 emissions and help compensate for emissions from sectors that are difficult to decarbonize, thus facilitating the achievement of net-zero emissions. CDR technologies encompass various conventional and novel methods, including afforestation, bioenergy with carbon capture and storage (BECCS), biochar soil amendment, direct air capture (DAC), enhanced rock weathering (ERW), and ocean alkalinity enhancement (Smith et al., 2024).

C-SINK is a four-year European-funded project that aims to build a standardized and transparent European CDR market with trustworthy accounting methodologies based on robust MRV pre-standards and policy strategies. Comprehensive scientific assessments will be made of the various CDR approaches in terms of their potential uptake of CO_2, their safety, and other impacts.

GLOSSARY

Basalt rocks: They are extrusive igneous rocks (volcanic) that are low in silica content, dark-coloured, and rich in Fe and Mg. Basalt usually exhibits a porphyritic structure with phenocrysts of olivine, pyroxene (augite), and feldspar in the matrix[1].

Carbonates: Include all forms of inorganic carbon, such as calcium and magnesium carbonates.

Carbon Dioxide Removal (CDR): Refers to activities that remove CO_2 from the atmosphere and store it permanently (IPCC, 2018).

Mafic and ultramafic rocks: Mafic and ultramafic rocks are rock types consisting predominantly of mafic (Mg- and Fe-rich) minerals (e.g., olivine, pyroxene, and amphibole) with a low content of silica. The ultramafic rocks are defined within an olivine, orthopyroxene, and clinopyroxene ternary diagram[2].

ERW PROCESS

Rocks and mining by-products or wastes are commonly composed of several minerals, or less frequently of one mineral type. When these are exposed to wind, rain, or waves at various temperatures, they are eroded, releasing dissolved ions into water in a natural process called weathering. During this process, atmospheric CO_2 reacts with water, forming a weak acid (carbonic acid or H_2CO_3), which causes mineral dissolution (Figure 1). If rocks contain high concentrations of Ca-, Mg-, and Fe-rich minerals (e.g., olivine, pyroxene, amphibole group minerals), they dissolve, releasing cations and anions in water. Several chemical reactions for mineral dissolution

[1] https://www.britannica.com/science/basalt

[2] https://geologyistheway.com/igneous/classification-of-ultramafic-rocks/

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and carbon sequestration are involved in the ERW process (Vandeginste et al., 2024). The carbonic acid dissociation in relation to pH is described in Figure 1.

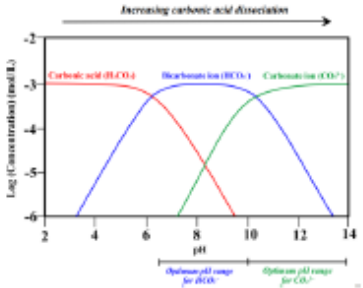


Figure 1. Influence of pH on carbonic acid dissociation in an idealised solution (modified after Rackley, 2017).

Mineral dissolution

Atmospheric CO_2 gas dissolves in water and forms carbonic acid (Equation 1-4). Bicarbonate and carbonate ions become available in the solution, the extent of which depends also on the pH of the water (Figure 1).

$$CO_{2\,(g)} \leftrightarrow CO_{2\,(aq)} \quad (1)$$

$$CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_{3\,(aq)} \quad (2)$$

$$H_2CO_{3\,(aq)} \leftrightarrow H^+_{\,(aq)} + HCO_3^-{}_{(aq)} \quad (3)$$

$$HCO_3^-{}_{(aq)} \leftrightarrow H^+_{\,(aq)} + CO_3^{2-}{}_{(aq)} \quad (4)$$

Then, the formation of carbonic acid aids in the dissolution of (ultra)mafic rocks and minerals and leads to the release of cations (Equation 5). The dissolution of these rocks and minerals will cause an increase in the pH of the water, and thus, a larger availability of bicarbonate and, in particular, carbonate ions. In this way, carbon is removed from the atmosphere and trapped as bicarbonate and carbonate ions in water.

$$Mg_2Si_2O_5(OH)_{4\,(s)} + 6H^+_{\,(aq)} \rightarrow 3Mg^{2+}_{\,(aq)} + 2SiO_{2\,(s)} + 5H_2O \quad (5)$$

Carbonate sequestration:

CDR by ERW of crushed ultramafic rocks (e.g. olivine) applied to soils can be calculated via two pathways (Beerling et al. 2020):

Pathway 1) the transfer of weathered base cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) from soil drainage waters to surface waters that are charge balanced by the formation of HCO_3^- ions and transported to the ocean Equation (6).

$$CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4 \quad (6)$$

Pathway 2: The formation of pedogenic carbonates is described by Equation (7) for calcium carbonate formation.

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (7)$$

ERW DEPLOYMENT PROCESS

The ERW stepwise deployment process, including critical control points (CCP) and key performance indicators (KPI), are illustrated in Figure 2.

1) Source Materials: The physicochemical properties of the source material are the first factor that controls the carbon dioxide sequestration potential of ERW. These include chemical composition, mineralogy, and particle size.

2) Comminution: Material that is acquired finely grained may skip the process of comminution and be readily available for transport. Should comminution be required, this generates an extra cost- and energy-intensive step.

3) Transport: The materials are transported to targeted locations for dispersion. These locations can be either arable lands or seashores, providing different concomitant benefits. In C-SINK, the CDR potential of mining wastes in situ is also tested since the

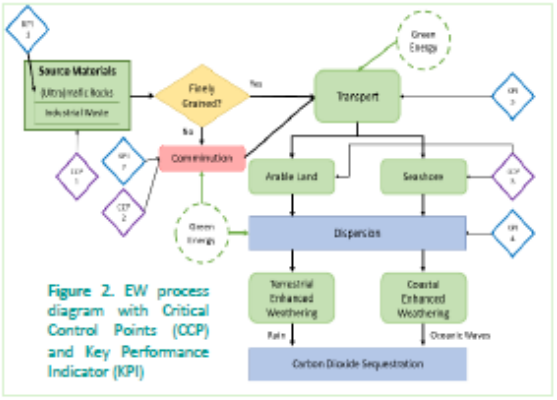


Figure 2. EW process diagram with Critical Control Points (CCP) and Key Performance Indicator (KPI)

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use of these wastes avoids extra costs and transport emissions.

4) Dispersion: Dispersion on arable land could increase crop growth due to nutrient addition, while dispersion on the seashore could reap the benefits of wave action for faster dissolution.

5) Carbon dioxide sequestration: once dissolved, source materials increase the alkalinity of the solution, thereby creating a potential for CO_2 to be sequestered as bicarbonate or carbonate minerals. Using green energy for comminution, transportation, and dispersion processes is necessary to increase CDR and meet climate targets.

ERW PARAMETERS INFLUENCING THE CDR POTENTIAL

Different researchers such as Strefler et al., (2018) Beerling et al., (2020) Smet et al., (2021), and Bullock et al., (2023) agree that the CDR potential through ERW depends on several parameters such as the type of rocks, grain size and surface, temperature, soil type, and climate factor, pH, and particular plant species.

❖ Type of rocks derived from mine wastes and other by-products.

Olivine is the most abundant and fastest-weathering magnesium silicate mineral on Earth (Smet et al., 2021, Bullock et al., 2023). This means that olivine-rich rocks have the highest potential for both carbon dioxide removal and soil fertility improvement.

Ultramafic igneous rocks (e.g. peridotite, dunite, harzburgite, kimberlite) consist mostly of olivine, and their metamorphic equivalents (e.g. serpentinite rock) are composed of serpentine, along with other Fe-Mg silicate minerals. These rocks have the highest CDR potential (up to 0.8 ton CO_2 per ton of applied ultramafic rock dust), but they contain low concentrations of nutrients and high heavy metals content (e.g. Ni and Cr), which can be an environmental risk (Strefler et al., 2018).

Mafic rocks (e.g. basalt, gabbro, diabase) have a lower CDR potential (about 0.3 ton CO_2 per ton of applied basalt) as they contain less olivine and Fe-Mg silicate minerals (Strefler et al., 2018). However, they contain a range of other minerals that release Ca, Na, K, and P upon dissolution, making them excellent natural fertilizers – and their Ni and Cr contents are not as high as for ultramafic rocks.

❖ Grain size and surface

The reactive surface area of the CDR material is increased by reducing the grain size, therefore increasing the rate of weathering (Beerling et al., 2020, Smet et al., 2021). However, the energy and cost involved with crushing and grinding (ultra)mafic rocks put limitations on the achievable grain size. Therefore, using mining wastes is highly recommended since it decreases the energy requirements of ERW as extra comminution is not necessary.

❖ Soil type and climate

Renforth (2012) and Smet et al. (2021) showed that high temperatures accelerate the weathering process (e.g. tropical climate) and intense rainfall is crucial since water is necessary for the chemical reaction to take place because it provides a sufficient supply of CO_2.

❖ Plant species

Afforestation can considerably increase the weathering rate of applied silicate rock powders (Smet et al., 2021). Chemical, physical, and biological soil properties are very different near plant roots. Microorganisms also boost the physical and chemical breakdown of silicate grains in the soil (Calabrese, 2022).

ERW TIMEFRAME FOR CDR

The removal of CO_2 through ERW, thus through a mineral carbonation process, is not immediate (Chiquier et al., 2022). Carbonation rates range from a few months to a few decades (Renforth, 2012; Strefler et al., 2018 and Beerling et al., 2020). Bullock et al. (2023) suggested 100 years, while Smet et al. (2021) referred to rock weathering not only removing CO_2 from the atmosphere but also initiating permanent carbon sequestration. However, Hangx &

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Spiers (2009) estimated a timeframe of 23 years for the full dissolution of 10 µm olivine particles on beaches. This duration increases to 233 years for a grain size of 100 µm.

C-SINK field trial data point out that a multitude of factors such as grain size, climatic conditions, rate of mineral application, etc., affect the timescales in which CO_2 removal can be achieved by ERW.

REVERSAL RISK

C-SINK ERW upscaling work considers that mineral precipitates are a relatively stable form of CO_2 removal. In the case of calcium carbonate formation, it is susceptible to re-dissolution (and thus CO_2 release) if it encounters acidic fluids. Therefore, the risk of reversal can be high in such a scenario. However, the environment where the mineral precipitates (e.g., deep in the ground) can reduce this risk. Strefler et al. (2018) suggested that compared to other CDR technologies, ERW has low technical risks.

COSTS, TRL

According to Schuiling & Krijgsman, (2006), the cost of the technology is estimated to be on the order of 14 €/t of CO_2. It is supposed to be a competitive price compared to the other technology solutions. However, an economic cost assessment by Strefler et al. (2018) indicated that ERW costs were below 67 € t rock^{-1} for grain sizes around 20 μm, leading to costs of carbon removal around 57 € per tCO_2 for dunite and around 191 € per tCO_2 for basalt. This is higher than most recent cost estimates for afforestation (23 € tCO_2) and BECCS (34 € tCO_2), but still lower than expected costs for direct air capture (412–546 € tCO_2). If co-benefits from nutrient supply or soil improvement are taken into account, the competitiveness of EW will further increase. Subsequently, Geden & Schenuit (2020) mentioned that the method's potential is estimated to be 2–4 Gt CO_2, at 48–192 € per tonne of CO_2 removed.

Finally, C-SINK experts agree with Beerling et al., (2020) related to the cost assessment estimating that ERW could cost between 72-239 €/tonne theoretically. However, within the C-SINK project, a few field trials will be developed to have assessments of the MRV cost and removals. Regarding TRL, Smith et al., (2023) ranked 3-4 for EW, which is considered a medium level. Therefore, a TRL7 will be conducted in the C-SINK project.

TYPICAL SCALE

No typical scale of CO_2 has been found in the literature because of incongruences and disagreements between researchers. These incongruences were summarised by Samaniego et al. (2023), and since the IPCC suggested a range for the potential to remove carbon of 0.72 to 95 $GtCO_2$ yr^{-1}, recent enhanced weathering experiments have suggested the technique may be up to three times less efficient than previously suggested by Amann et al. (2020).

On the other hand, Hangx & Spiers (2009) estimated that the weathering of 1 tonne of mafic (e.g. basalt) and ultramafic rocks (e.g. dunite) can remove ~ 0.3 and 0.8 tonnes of CO_2, respectively, indicating a considerable overall theoretical potential.

Overall, enhanced weathering is still a relatively new CDR technology to the industry and one of the major unknowns in this technology is the actual amount and timescale of CO_2 sequestered.

SCALABILITY AND LIMITING FACTORS

As for technical and operational factors, Samaniego et al. (2023) summarised the scalability of ERW in terms of limiting factors. Although the ERW technology has been put into practice in several case studies, it is classified as a slow solution due to the geochemical reactions of the process to transform some minerals into carbonates. Besides, the potential CO_2 removal is a crucial uncertainty that should be solved for further scaling. However, there may be a preference for the use of mining by-products or wastes for enhanced weathering rather than the exploitation of new mines to access materials.

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Regarding policies and regulations, if ERW would be deployed at a significant scale, new international mechanisms for monitoring, verification, and reporting, including mechanisms that account for the transboundary effects of the approach would be required (Samaniego et al., 2023). Also, new policies for transporting and handling 'waste' or new classification of mine waste to be a 'by-product'.

Besides, researchers such as Beerling et al. (2020) extrapolated laboratory weathering rates to the field scale to calculate CDR rates by enhanced rock weathering, ERW technology applying Monte Carlo analysis, a well-recognised method. Recently, ERW as CDR-T has been upscaled and modelled by Beerling et al. (2024) in the US Corn Belt with agronomic benefits.

In short, the limitations to the scalability of ERW are controlled by the scenarios in which it is implemented. Some mineral and rock sources are widely available and can be applied close to the source site, which reduces transportation costs. The most favourable is the use of mine waste tailings being applied on site, which avoids the need for comminution as well as transportation.

EW PILOTS WITHIN THE C-SINK PROJECT

The C-SINK project investigates ERW as a CDR technology through two distinct field trials in Spain (David mine) and Finland (Kevitsa mine), where Monitoring, Reporting, and Verification (MRV) is carried out in situ within active mine sites. Both trials test MRV under real, open-system conditions, focusing on transparent, scalable, and long-term sustainable removals through atmospheric CO_2 conversion into stable carbonate forms.

David Mine (Galicia, Spain): Field trials at David mine (NW Spain) operated by PASEK MINERALES S.A.U. focus on the CDR efficiency of dunite waste produced in the quarry, compared with artificial soil and biochar synergies for maximizing CO_2 capture and sequestration under a mild oceanic climate. Artificial soils produced by EDAFOTEC S.L. contain bio-stabilized residues and construction/demolition wastes enhancing CO_2 capture, whereas biochar produced by IBERO MASSA FLORESTAL S.A. promotes stable carbon storage and other co-benefits in soil properties.

The field trial parcels configuration is the following (Figure 3):

- Plot 1: Artificial Soil
- Plot 2: Artificial Soil and biochar
- Plot 3: Artificial Soil with dunite
- Plot 4: Artificial Soil, biochar, and dunite
- Plot 5: ERW (dunite), vegetation
- Plot 6: ERW (dunite) *control plot*

Various soil variables, including soil carbon in different chemical forms, are monitored over 24 months in the six experimental plots, including the control and a vegetated plot. Unmanned Aerial Vehicle Remote Sensing (UAV-RS) technologies will be utilized to establish correlations between chemical measurements of different organic carbon fractions and multispectral images acquired. The data collected during

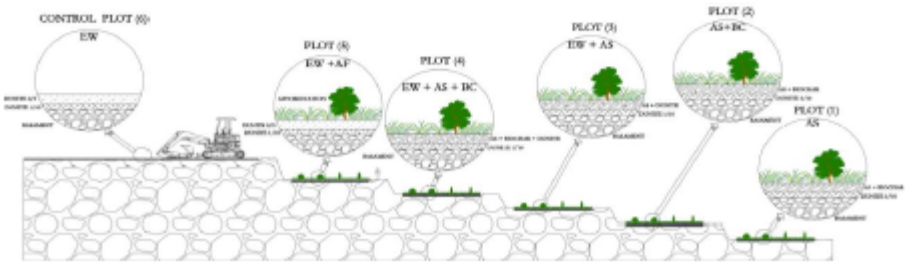


Figure 3. C-SINK field trial set up at David mine in Spain (PASEK MINERALES S.A.U.) in which ERW technology is tested for CDR.

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monitoring will enable the use of artificial soil and ERW under open system conditions. The following physical-chemical parameters are overseen over 24 months:

1. Physical characteristics: Particle size distribution, specific Surface (BET), Bulk density.
2. Chemical characteristics: pH in water, mineralogical analysis (X-ray diffraction), electrical conductivity (EC), chemistry analysis includes trace elements such as As, B, Ca, Cd, Cl, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Ni, Pb, S, Se and Zn.
3. Specific carbon analyses: Total inorganic carbon, stable isotopes of C and O with an isotope ratio mass spectrometer (IRMS), inorganic carbon evaluation (DRX, Microscopy, etc.), total Soil Organic carbon (SOC) fractioning of labile and stable C-pools, remote sensing evaluation of organic carbon evolution using UAV (drones) and multispectral.

<u>Kevitsa Mine (Sodankylä, Finland):</u> At Kevitsa, an open-pit nickel, copper, gold, platinum, and palladium mine (N Finland) operated by BOLIDEN AB, field trials focus on the carbonation potential of ultramafic waste rocks and tailings under arctic conditions. An experimental cell is constructed on the west side of the Kevitsa tailings storage facility (TSF).

Figure 4 shows the cross-sectional view of the test cell design. The test cell is placed topographically above the level of tailings placement within the TSF and is constructed with ~2m berm/bund using mine waste rock. The cell is filled with low-sulfur beach tailings sourced from the tailings in situ at the existing TSF.

The tailings material is composed of Mg- and Ca-bearing silicate minerals that capture CO_2 due to the dissolution of reactive silicate minerals to precipitate secondary carbonate minerals. The cell is instrumented with monitoring ports that contain pH, temperature, moisture content/electric conductivity (EC), O_2, and CO_2 probes and sensors at various depths. A gas flux box is placed on top of the cell tailings to monitor O_2 and CO_2 levels at the surface of the tailings. A drain coil is placed at the base to collect leachate for chemical analysis. Additionally, a control monitoring port, dug in the moraine ground, is also instrumented with the same sensors in the tailings test cell to produce data for comparative analysis with the results from the tailings test cell. Key parameters to quantify CDR at Kevitsa mine are:

- Alkalinity (pH sensor)
- Gas fluxes (O_2 & CO_2 sensors)
- Electrical conductivity (EC sensor)

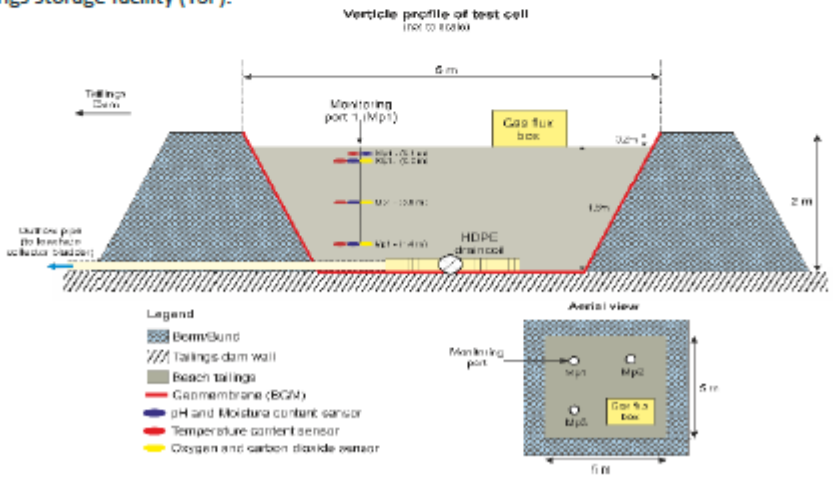


Figure 4. Cell design and setup of the ERW field trial at Kevitsa mine in Finland (BOLIDEN AB), containing a monitoring port and sensors at various depths.

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- Climate (weather station on site)
- Dissolved inorganic carbon (DIC) from leachate
- Major and trace elements (XRF & ICP-MS) – from leachate.

POTENTIAL RISKS

ERW could have some barriers or possible problematic side effects, which do not allow its scaling and should be solved. Some of these were discussed in a range of studies (Hartmann et al., 2013; Strefler et al., 2018; Reershemius, et al., 2023; Samaniego et al., 2023; Vandeginste et al., 2024) and are summarised below:

- Dust generation due to fine particulate pollution
- Nickel and chromium accumulation and its release into aquatic and marine systems during dissolution.
- Change in pH of soils and surface waters (streams, rivers, lakes), affecting terrestrial and aquatic ecosystems.
- Change in Si concentration of surface waters, affecting ecosystems via altered nutrient ratios
- Environmental costs of up to three orders of magnitude increase in olivine mining, globally.

CO-BENEFITS

Previous studies (Schuiling & Krijgsman, 2006; Hartmann et al., 2013; Reershemius, et al., 2023) suggested that ERW as CDR-T has potential advantages and co-benefits, such as:

- A low technological barrier to implementation at scale.
- Long-term (>1000 years) storage of carbon compared to organic reservoirs.
- Increasing pH of ocean waters, counteracting CO_2-induced acidification

a) Supply of Si to coastal oceans. May counteract Si limitation and decrease harmful algal blooms.

b) It may act as "ocean fertilization" to enhance the sequestration of atmospheric CO_2 through the organic carbon biological pump.

- Supply of Si and other nutrients (principally Fe, Mn, P, K) to terrestrial ecosystems.

a) May increase terrestrial productivity and lead to greater sequestration of CO_2 in terrestrial biomass.

b) May increase crop production, providing additional income for farmers through CO_2 certificate trading and deacidification of soils where ERW feedstocks such as basalt rock can fill the same role as agricultural lime (currently a net source of CO_2 to the atmosphere).

- Several recent advances make the upscaling of ERW more likely through mechanistic modelling of weathering reactions in agricultural soils and modelling of hydrology affects ERW deployment.
- Laboratory experiments tracking the uptake of nutrients by plants and feedstock dissolution rates.

Finally, Eufrasio et al. (2022) indicated that ERW is competitive with other large-scale CDR strategies in terms of energy and water demands. More precisely, EW has potential co-benefits for improved food and soil security and reduced ocean acidification (Beerling et al., 2020) (Smet et al., 2021).

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10.4. Appendix D

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C-SINK Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

C-SINK– FACTSHEET LECTURE 4 DELIVERED BY ICAMCYL & UED

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T): BIOCHAR (BC)

INTRODUCTION

The urgency to address climate change was highlighted in the Paris Agreement in 2015 (United Nations, 2015), followed by a detailed assessment by the IPCC (IPCC, 2018b) based on scientific, technical, and socio-economic data available in the literature on global warming of 1.5°C and the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. Subsequently, the European Commission (EC) accepted that human activities (both industrial and domestic) have caused around 1°C of global warming to date, resulting in abrupt climate changes, and acknowledged that most countries, especially the highly industrialized ones, must take drastic measures to avoid disastrous impacts on public health and safety. The EC (European Commission, 2018a-773) additionally, it was agreed that CO_2 capture will be required in significant quantities through land solutions and other technological solutions such as ocean alkalinisation, biochar (BC), direct capture of CO_2 in the air, bioenergy with CO_2 capture and storage (BECCS), etc., to achieve net zero greenhouse gas (GHG) emissions by the end of the century.

The C-SINK project, funded by Horizon Europe, aims to lay the foundations for a standardized, transparent European CDR market with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

WHAT IS CARBON DIOXIDE REMOVAL (CDR)?

CDR refers to activities that remove CO_2 from the atmosphere and store it permanently (IPCC, 2018a). Available CDR technologies can be grouped into nature-based and technology-based removals (Meyer-Ohlendorf, 2020), in which nature-based methods enhance biological sinks of CO_2 (e.g., afforestation (AF) and reforestation (RF), soil carbon sequestration (SCS). Technology-based removals employ chemical engineering to achieve long-term removal and storage. Current techniques include Biomass Energy with Carbon Capture, Enhanced Weathering, improved soil quality, or biochar (Ornelas et al., 2023).

WHAT IS BIOCHAR?

Biochar is the solid residue of biomass pyrolysis, i.e., a pyrogenic carbonaceous material resulting from the thermochemical conversion of biomass at elevated temperatures between 400-1200 °C in an oxygen-free or oxygen-limited atmosphere[1].



Figure 1. Feedstock types in the biochar process. UKBRC (2018). *Standard Biochars*. Retrieved [2025], from https://www.biochar.ac.uk/standard_materials.php

DEFINING CO_2 REMOVAL FROM A BC STANDPOINT

The carbon sequestration potential of biochar is based on stopping the release

[1] https://era.ed.ac.uk/handle/1842/39193

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of CO_2 from natural biomass decomposition through carbon stabilisation in the form of solid biochar. Organic carbon concentrated in biochar represents the removed CO_2 after deducting production emissions. The recalcitrance or degradation of the organic carbon content of biochar determines the CDR potential.

BIOCHAR PRODUCTION/ROUTES

According to C-SINK experts, biochar production is currently focused on three main routes with different target products. Slow pyrolysis is aimed at maximizing biochar production, while biomass gasification maximizes energy production with biochar as a potential co-product. Biomass intermediate pyrolysis polygeneration (BIPP) optimizes for biochar, fuel, and electricity production. All 3 approaches show promising industrial potential under different circumstances and should be included as base scenarios. Within these 3 approaches, a wide array of different combinations exists, which are mainly based on different mass flows (based on differences in feedstocks, processing conditions, or energy recovery).

Despite the different scenarios for biochar production, once the biochar is produced, its application adds additional – but separated - scenarios as the application of biochar can be as a soil amendment with ensured carbon sequestration, or as a material input in other products, which might not count as a carbon sequestration route.

DEFINITION OF EACH PROCESS-STEP

1. Biomass harvest and transport to the pyrolysis plant: Ideally, this involves waste biomass streams consisting of industrial residues such as sawdust or agricultural residues (i.e., straw, chippings, manure). See Figure 2.

2. Processing: Processing requirements for biomass depend on individual reactor configurations for the pyrolysis technology used and the utilized feedstock type, form, and condition. Generally, this involves size reduction (chipping, cutting, milling), densification (pelletizing), and/or drying to a moisture content suitable for the utilized reactor technology.

3. Pyrolysis: The actual pyrolysis reactor heats the biomass to the target temperature of the technology and breaks the material down into three product fractions (biochar, bio-oil, and pyrogas). The fraction between these portions is not independent of the employed technology type and economic considerations. For example, gasification is a biochar production process in which the main target product is a combustible gas utilized as an energy carrier, in contrast to slow pyrolysis routes in which biochar is the main product.

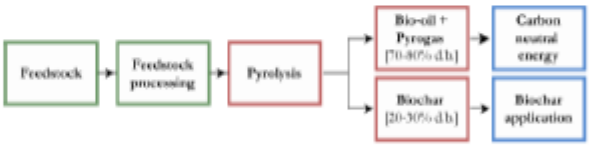


Figure 2. Simplified process diagram for slow pyrolysis systems with energy utilisation of co-products (green – biomass sourcing phase; red – biomass conversion phase; blue – application phase). Source: Wurzer, C. & Masek, O. (2024).

4. Pyrolysis by-products:
- ❖ Syngas: the product gas produced from the decomposition of biomass can be utilized as an energy source to heat the reactor, as a stand-alone product, or as an input material to produce electricity.
- ❖ Pyro-oil: the liquid fraction of biomass decomposition can be utilized as an energy carrier or directly combusted to provide heat.
- ❖ Biochar

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5. Biochar processing: Biochar processing involves cooling the product at the outlet of the reactor to ambient, size reduction or densification procedures (i.e., grinding, milling, palletization), or mixing with additional materials to produce bespoke products (i.e., compost, nutrients, fertilizers).

6. Soil application: The main application of biochar is within agricultural soils and requires spreading on land. Alternative application routes can be found as a substitute material in material production, such as concrete or plastics.

WHAT IS THE CURRENT STATE OF THE TECHNOLOGY?

Biochar production and utilisation are already in industrial operation worldwide, with over 170 operational plants within Europe alone. This highlights the maturity of biochar technology to date, with several turn-key technology providers available. Biochar's carbon sequestration potential was estimated in a recent study by Lefebvre et al. (2024) at 6.9 Mt CO_2e year−1, representing ~ 6.2% of current emissions in the covered 155 countries. European biomass availability is also significant, with approximately 452 Mt of biomass available annually, representing around 121 Mt of biochar or 245 Mt of CO_2e year-1.

PERMANENCE

The most common timeframe utilised to model CO_2-removal through biochar technology is 100 years (Woolf et al., 2021) and (Chiquier et al., 2022). Regarding the biochar time factor in removing, direct CDR effects of biochar are immediate at the point of production (if not burned subsequently). Indirect effects, such as increasing soil organic stocks beyond biochar carbon might take effect over longer periods.

According to (Schmidt et al., 2022) biochars generally consist of two pools– semi-persistent (SPC) and persistent carbon (See Figure 3). The higher the production temperature- the more persistent the carbon. Polyaromatic carbon will be stable on geological timescales and was shown to comprise the majority of high-temperature biochars, which are the common output of current industrial reactors within the European Union (Sanei et al., 2024).

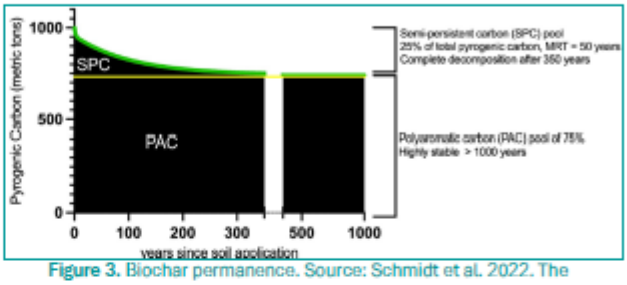


Figure 3. Biochar permanence. Source: Schmidt et al. 2022. The permanence of soil-applied biochar. The Biochar Journal.

Due to the dramatically enhanced carbon stability of biochar, biomass carbon is moved from the short-lived biosphere into geosphere timeframes, representing a shift in carbon residence times beyond timeframes relevant for human intervention to tackle climate change (centuries to millennia)(Chiaramonti et al., 2025).

REVERSAL RISK

Biochar presents a comparably low risk of unexpected leakage according to the latest research demonstrating biochar's permanence (Chiaramonti et al., 2024) (Sanei et al., 2024). While biochar carbon consists of a labile and a stable fraction, stable biochar carbon is likely sequestered for geological timescales if produced in modern reactors. The labile fraction degrades more rapidly (i.e., within a century), but represents minor parts of biochar carbon. Reversal risks can be present if production temperatures are insufficient for carbon

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stabilisation within biochar, but are omitted in industrial reactors. Besides carbon degradation, the combustibility of biochar is an additional risk; however, after soil application, the risk of reversal through wildfires is minimal due to incorporation within the soil matrix.

COSTS, TRL, AND TYPICAL SCALE

Generalized biochar cost estimations are unreliable due to the many possible combinations of feedstock, production technology, and application (Campion et al., 2023). Key cost factors vary widely, influenced by location, scale of operation, whether waste or virgin materials are used, and the specific final product (e.g., agricultural char versus energy co-products). Table 1 shows biochar price estimation from academic literature in USD per ton from academic literature and voluntary carbon credit marketplaces.

The European Biochar Industry (EBI)[2] classifies biochar production plants into small (100-199t), medium (200-499t), large (500-1999t), very large (2kt-5kt), and industrial (>5kt) production volume per year. Calculating the CO_2 removal potential requires the application of an average CO_2 removal multiplicator of 2-2.6.

Table 1. Biochar price estimation. Source: Wurzer, C. & Masek, O. (2024).

Biochar cost estimation [USD per ton of biochar]				
Reference	Region	Min	Max	Mean
Nematian et al. (2021)	North America	450	1850	
Stefan Jirka and Tomlinson (2015)	North America			1500
Alhashimi and Aktas (2017)	North America	800	1780	
Bergman et al. (2023)	North America	580	1050	
Ahmed et al. (2016)	North America	500	600	
Sessions et al. (2019)	North America	500	600	
Nematian et al. (2021)	North America	571	1455	
Kim et al. (2015)	North America			330
Sorensen and Lamb (2018)	North America			290
Struhs et al. (2020)	North America			240
Dutta and Raghavan (2014)	North America	40	50	
Liu et al. (2022)	China	790	930	
Xiao et al. (2020)	China			20
Shackley et al. (2011)	UK	150	600	
Latawiec et al. (2021)	Poland			85
Ahmed et al. (2016)	Spain			75
Robb and Darguach (2018)	Australia			265
Wrobel-Tobiszewska et al. (2015)	Australia			1000
Dickinson et al. (2015)	Sub-Saharan Africa	100	165	
Ahmed et al. (2016)	Sub-Saharan Africa			100

[2] https://www.biochar-industry.com/

BIOCHAR PRODUCERS WITHIN THE C-SINK CONSORTIUM



Figure 4. Ibero Massa Florestal, S.A (IMFLORESTAL). It is located in Oliveira de Azeméis, Portugal. Capacity: 5000 tons/year.

IMFLORESTAL is a pioneering company in producing and commercializing biocharcoal for domestic and agricultural use. It uses an innovative green technology of its own development for transforming agricultural and forest biomass through slow pyrolysis. With a current production of biochar derived from woody invasive species of 1000 tons/year.



Figure 5. Pyrogenesys in Birmingham, UK.

The innovative technology provided by the company converts waste grain and hops from brewing and dried distillers' grains (DDGS) from the whisky industry into heat to supply to the brewery, as well as into bio-oil and glucose. The approach will improve energy efficiency and contribute to decarbonization by reducing dependency on fossil fuel-derived process heat (natural gas) and developing potential uses for coproduct streams.

NEGATIVE EFFECTS

❖ Priming effect: Biochar has the potential to either increase or decrease soil carbon mineralisation (positive or negative priming). This effect is typically

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short-lived due to initial disturbance of soil microbiology (Wang et al. 2016).

- Particulate and greenhouse gas emissions from biochar production; biodiversity and carbon stock loss if from unsustainable biomass harvest (Smith et al., 2023).
- Biochar production can affect land-use conflicts as it requires biomass feedstocks and can either in or exclude the local population depending on the intervention's design (Honegger et al., 2021).

Biochar might change the albedo effect of surfaces (Wurzer, C. & Masek, O., 2024).

CO-EFFECTS

- Better crop yields (Smith et al., 2023).
- Biochar use in agricultural practices can enhance agricultural resilience (Honegger et al., 2021).
- Combining with mining residues shows positive results for the reduction of metal (Smet et al., 2021) (Fabbri et al., 2021).
- Substitution of fossil materials or materials with a high carbon footprint [cement, sand].
- As a soil amendment, biochar (Wallace et al., 2012) (Geden & Schenuit, 2020) (Fabbri et al., 2021) (Ruiz et al., 2023) can contribute to 1) add nutrients and improve the uptake of applied fertilizers; 2) increase the properties of sandy soils through water retention improvements; and 3) increases microbial activity, enhancing agronomic yield.

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10.5. Appendix E

AS - L1

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C-SINK– FACTSHEET 6 DELIVERED BY ISMC, UNIOVI, PAS, LURTEK, ICAMCYL

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR): ARTIFICIAL SOILS

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, **European leaders endorsed the objective of achieving a climate-neutral Europe (EU) by 2050**. This followed the commitments made by all European member states that ratified the Paris Agreement in 2015 (United Nations Framework Convention on Climate Change [UNFCCC], 2016). The Agreement is a legally binding international treaty that sets long-term goals to guide all nations to substantially reduce greenhouse gas (GHG) emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, recognizing that this would significantly **reduce the risks and impacts of climate change**.

The European Climate Law (European Parliament & Council, 2021) proposed in 2020, as a part of the European Green Deal (European Commission, 2019), the strategy through which to achieve EU climate neutrality by 2050. It legally binds the EU to reduce net greenhouse gas (GHG) emissions. It establishes an intermediate milestone, requiring a reduction in net greenhouse gas emissions of at least 55% by 2030 compared with 1990 levels. To adopt these ambitious climate goals, particularly with its proposed 90% net GHG reduction target for 2040, the implementation of **technologies, practices, and approaches for actively carbon dioxide removal (CDR) and durably store existing carbon dioxide from the atmosphere and drastically cutting emissions** by switching to renewables and improving energy efficiency. Combining emission reductions with carbon removal is essential because cutting emissions alone is not enough to reverse current atmospheric CO_2 levels, to meet 2050 net-zero and net-negative emission goals.

CDR is primarily needed to offset emissions from hard-to-decarbonize sectors (like cement, aviation, heavy industry) that cannot be eliminated entirely, and to counter declining natural carbon sinks, making **CDR a climate necessity and strategic opportunity for jobs and innovation**, supported by EU policies like the Carbon Removal Certification Framework (CRCF).

This involves developing strategies for both land-based (forests, agriculture) and industrial (Direct Air Capture, Bioenergy with CCS) methods, setting up certification frameworks like the EU's Carbon Removals Regulation, and creating incentives through mechanisms like the EU Emissions Trading System (ETS) to scale up CDR as a vital economic opportunity and strategic necessity. The EU ETS is a cornerstone of the Union's climate policy and constitutes its key tool for reducing greenhouse gas emissions in a cost-effective way.

The C-SINK project funded by Horizon Europe aims to establish the foundations to build a standardized and transparent European CDR market to contribute to the implementation of climate change mitigation measurements through the responsible employment of CDR technologies, by complementing existing EU and international mitigation efforts with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR technologies is an umbrella term for techniques that can be used to capture

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carbon dioxide (CO_2) from the atmosphere and store durably in geological, terrestrial, or ocean reservoirs, or in products with varying CO_2 storage durations from decades to millennia (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

CDR technologies are divided into Nature-Based Solutions, Engineered Solutions and Hybrid Solutions:

- Nature-Based Solutions leverage natural processes, such as afforestation /reforestation (planting trees) and soil carbon sequestration, to absorb and store CO_2.
- Engineered Solutions use advanced technologies and chemical processes, such as Direct Air Capture (DAC) and carbon mineralization, to remove and durably store CO_2.
- Hybrid Solutions combine aspects of both, often using natural systems to capture the CO_2 (e.g., biomass) and engineered processes to ensure more durable storage.

Nature-based solutions stand out as more cost-effective and viable in the short run, while some technological alternatives have potential to become more relevant later this century. The European Commission recognises the crucial role of CDR and intends to focus on nature-based options.

Examples of CDR include:

- Afforestation/reforestation: transforming non-forested areas into woodland by planting, trees to capture and store CO_2.
- Soil carbon sequestration: natural process where plants convert CO_2 from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration: rewetting and revegetation of degraded peatlands can capture CO_2, with CO_2 stored in soils.
- Biochar: a charcoal-like substance created from plant matter which can store carbon; it can be used on agricultural land (with benefits for the soil and crop yields), or in products.
- Enhanced rock weathering: crushed silicate rock such as basalt can be spread on agricultural land (with benefits for the soil and crop yields) to capture and store CO2.
- Bioenergy with Carbon Capture and Storage (BECCS): biomass (purpose-grown crops or agricultural/forestry residues) captures CO_2 from the atmosphere as it grows; when the biomass is burned to generate electricity or heat, CO_2 is captured and stored.
- Direct Air Carbon Capture and Storage (DACCS): captures CO_2 from the atmosphere using industrial chemical processes and stores it durably in geological storage or products.
- Marine-based techniques such as ocean alkalisation and coastal wetland management: there are a variety of methods that use geochemical or biological capture, and various forms of storage. A subset of CDR methods such as BECCS and DACCS make use of Carbon Capture and Storage (CCS) technologies to deliver net negative emissions (that is, to reduce overall levels of carbon dioxide in the atmosphere) but it is important to note that applying CCS technologies to emissions from fossil fuels can never result in carbon dioxide removal from the atmosphere. Therefore, the terms CDR and CCS are not interchangeable.

ARTIFICIAL SOILS

Natural soils retain and remove atmospheric CO_2 through the interaction of the soil-plant system, which plant absorb CO_2 from the atmosphere and convert it into organic matter when plant material decomposes, some of this carbon is incorporated into the soil as soil organic carbon (SOC) and other via is the hydrological/hydrogeological systems as inorganic C (bicarbonate in solution or carbonate minerals) (Beerling et

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al., 2020). Globally, it was recognized the significance of using soil processes to remove atmospheric CO_2 (Renforth et al., 2011), given that soil represents a carbon pool of up to 2,700 Gt in the top meter of soil globally, in the world's soils which is twice that of the atmosphere (730 Gt C) (Lal, 2003).

According to estimates from Sanderman et al. (2017) for the year 2010, the global SOC stocks were 1,824 Pg C in the upper 1 m of soil, and the global SIC stock was estimated at approximately 750 Pg in the top 1 m (Batjes, 1996) and more than 2300 Pg in the top 2 m (Le Quéré et al., 2016, Zamanian et al., 2021, Huang et al., 2021), which is similar to the organic carbon stocks found in the top 2 m of soil ~ 2400 Pg (Batjes, 1996). The potential of soils to store soil carbon and therefore its persistence in soils is the result of of functional complexity arising from the interplay between spatial and temporal variation in molecular diversity and composition (Lehmann et al., 2020). The removal process of carbon from the biological carbon cycle involves two processes: carbonation (i.e. the formation of paedogenic carbonate minerals in soils) and enhanced rock weathering (ERW).

In the context of carbon removal captured in soil in organic and inorganic form, artificial soils designed with two purposes **carbon capture and recycling waste**.

Artificial soils are engineered soils created by combining selected organic and inorganic waste materials to produce a functional and healthy soil. The specific composition varies according to local resource availability and the desired physic-chemical properties. Typical components may include manure, sewage sludge, pruning residues, sawdust, biomass combustion ashes, paper mill sludge, food waste, and construction and demolition waste (CDW).

The final mixture is carefully designed to meet soil health criteria such as appropriate pH, nutrient availability, structure, and texture. Artificial soils can be used for a range of purposes, including the regeneration of areas where soil has been degraded or lost, land decontamination, biomass production and green infrastructure (Deeb et al., 2020).

Artificial soils are classified as Technosols because they contain more than 20% human-made materials by volume within the upper 100 cm of the soil profile (Schad, 2015). Technosols encompass a broad range of soil types, from mine tailings and construction waste fills to land surfaces covered by geomembranes. While many Technosols are initially of low quality due to their origin, they can be purposefully engineered to address environmental challenges and significantly enhance soil health (Figure 1).

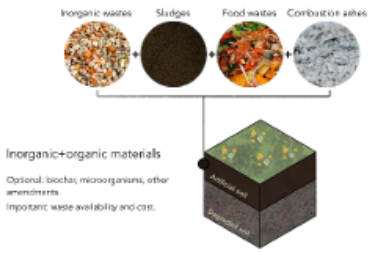


Figure 1. Diagram with examples of parent materials for artificial soil formulation

CURRENT STATE OF ARTIFICIAL SOILS AS CDR TECHNOLOGY

Artificial soils are currently situated largely in the research and development (R&D) stage, particularly with respect to their role as a carbon dioxide removal (CDR) option. While artificial soils are well established in land reclamation, urban landscaping, and brownfield restoration, their systematic design, monitoring, and optimisation for long-term carbon sequestration and stable ecosystem service delivery remain under active research.

At this stage, stability and predictability of policy and financial support are critical.

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Artificial soils require long-term experimentation to understand carbon accumulation rates, stabilization mechanisms (e.g. mineral-associated organic carbon formation), and interactions between physical structure, microbial activity, and vegetation. These processes unfold over years to decades, meaning that short funding cycles risk interrupting experiments before meaningful conclusions can be drawn. If R&D funding is withdrawn prematurely, artificial soil development risks becoming stranded before reaching demonstrable maturity or scalability.

Artificial soils also involve significant uncertainty regarding performance, as outcomes depend strongly on local materials (e.g. mine waste, construction residues, organic inputs), climate, and management practices. As a result, risk mitigation and risk absorption by public actors are essential, particularly where private actors have limited incentives to invest in uncertain, long-horizon soil-based CDR outcomes. Artificial soils still require upfront investment in site preparation, materials, monitoring, and long-term verification, with delayed and uncertain returns.

Beyond direct financial support, the deployment of artificial soils as a carbon dioxide removal (CDR) pathway requires enabling policy instruments and a stable regulatory environment to stimulate early-stage demand. This includes the formal inclusion of artificial soils within CDR research frameworks, land restoration and remediation policies, and soil carbon accounting and monitoring programmes. Explicit policy recognition of artificial soils as a credible CDR option would reduce institutional uncertainty, improve investment confidence, and accelerate technological development during the pre-commercial phase.

Artificial soils are currently transitioning into a demonstration phase, where pilot projects move from controlled research settings to real-world applications, such as degraded land reclamation, mining sites, infrastructure corridors, and urban environments. At this stage, considerations of scale become increasingly important; however, capital deployment remains high-risk due to persistent uncertainties related to long-term carbon stability, permanence, and the robustness and standardisation of monitoring, reporting, and verification (MRV) protocols.

Demonstration projects typically involve hectare-scale deployments, integration of heterogeneous waste streams, and testing of monitoring, reporting, and verification (MRV) approaches under operational conditions. These projects are essential to bridge the gap between laboratory-scale understanding and broader deployment, yet they often lack immediate revenue streams, making them highly dependent on continued public support.

Political and social support are particularly important at this stage. Artificial soils often rely on the reuse of secondary materials (e.g. mine waste, construction residues, organic by-products), which can raise regulatory, public perception, and social acceptance challenges. Strong institutional backing can help ensure continuity of incentive mechanisms, facilitate permitting, and encourage early adopters such as municipalities, landowners, and industrial site operators.

Demonstration-stage support should therefore prioritise pilot funding, risk-sharing instruments, and public procurement, as well as visibility and learning effects. Successful demonstration projects can help reduce uncertainty, build trust among stakeholders, and establish credible performance benchmarks that are necessary for progression toward maturity.

In the mature stage, artificial soils would be deployed at scale as a recognised and reliable CDR and land management option, with scale becoming the dominant

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imperative. At this point, artificial soils would demonstrate predictable carbon sequestration performance, robust MRV methodologies, and co-benefits such as soil restoration, biodiversity enhancement, and reduced waste disposal.

For maturity to be reached, revenue streams must be sufficient to sustain deployment, including the costs of construction, maintenance, and long-term monitoring. Revenues could be drawn from a mix of public and private sources, land restoration funding, infrastructure development budgets, and circular economy incentives tied to waste valorisation. As deployment scales up, efficiency gains and learning effects should reduce per-unit costs, improving competitiveness relative to alternative CDR options.

Cost-effectiveness becomes increasingly important at this stage, given the potentially large land areas involved. Support mechanisms should therefore prioritise artificial soil applications while also accounting for additional benefits (e.g. remediation of degraded land, reduced erosion, enhanced ecosystem services) and potential trade-offs (e.g. material transport emissions or land-use conflicts).

Despite maturity, stability remains a core requirement. Incentive mechanisms must be durable, predictable, and capable of operating over multi-decadal timescales, reflecting the long-term nature of soil carbon storage. Over time, support should transition toward self-sustaining approaches, where artificial soils are integrated into standard land management, infrastructure, and restoration practices, rather than relying solely on direct government subsidies.

ARTIFICIAL PILOT DEVELOPED WITHIN THE C-SINK PROJECT

A field pilot trial with artificial soil was carried out at Pasek mine within the framework of C-sink project. The purpose of this trial was to collect data to evaluate CDR with this technology by itself and when it is combined with EW and biochar. Six plots of 300 m^2 were implemented at David's Mine from Pasek Minerales, in Landoi, Cariño, Spain (Figures 2 and 3).



Figure 2 Aerial view of the pilot in February 2025 (4 artificial soil plots, 1 control where fertilizer was applied and trees and grasses were planted, and other second control plot that was unplanted).



Figure 3 pictures that compare artificial soil plot (without amendments) with control

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plot (where fertilizer was applied) in February 2025.

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10.6. Appendix F

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Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

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CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR): AFFORESTATION

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, **European leaders endorsed the objective of achieving a climate-neutral Europe (EU) by 2050**. This followed the commitments made by all European member states that ratified the Paris Agreement in 2015 (United Nations Framework Convention on Climate Change [UNFCCC], 2016). The Agreement is a legally binding international treaty that sets long-term goals to guide all nations to substantially reduce greenhouse gas (GHG) emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, recognizing that this would significantly **reduce the risks and impacts of climate change**.

The European Climate Law (European Parliament & Council, 2021) proposed in 2020, as a part of the European Green Deal (European Commission, 2019), the strategy through which to achieve EU climate neutrality by 2050. It legally binds the EU to reduce net greenhouse gas (GHG) emissions. It establishes an intermediate milestone, requiring a reduction in net greenhouse gas emissions of at least 55% by 2030 compared with 1990 levels. To adopt these ambitious climate goals, particularly with its proposed 90% net GHG reduction target for 2040, the implementation of **technologies, practices, and approaches for actively carbon dioxide remove (CDR) and durably store existing carbon dioxide from the atmosphere and drastically cutting emissions** by switching to renewables and improving energy efficiency. Combining emission reductions with carbon removal is essential because cutting emissions alone is not enough to reverse current atmospheric CO_2 levels, to meet 2050 net-zero and net-negative emission goals.

CDR is primarily needed to offset emissions from hard-to-decarbonize sectors (like cement, aviation, heavy industry) that cannot be eliminated entirely, and to counter declining natural carbon sinks, making **CDR a climate necessity and strategic opportunity for jobs and innovation**, supported by EU policies like the Carbon Removal Certification Framework (CRCF).

This involves developing strategies for both land-based (forests, agriculture) and industrial (Direct Air Capture, Bioenergy with CCS) methods, setting up certification frameworks like the EU's Carbon Removals Regulation, and creating incentives through mechanisms like the EU Emissions Trading System (ETS) to scale up CDR as a vital economic opportunity and strategic necessity. The EU ETS is a cornerstone of the Union's climate policy and constitutes its key tool for reducing greenhouse gas emissions in a cost-effective way.

The C-SINK project funded by Horizon Europe aims to establish the foundations to build a standardized and transparent European CDR market to contribute to the implementation of climate change mitigation measurements through the responsible employment of CDR technologies, by complementing existing EU and international mitigation efforts with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards and policy strategies.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

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CDR technologies is an umbrella term for techniques that can be used to capture carbon dioxide (CO_2) from the atmosphere and store durably in geological, terrestrial, or ocean reservoirs, or in products with varying CO_2 storage durations from decades to millennia (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

CDR technologies are divided into Nature-Based Solutions, Engineered Solutions and Hybrid Solutions:

- Nature-Based Solutions leverage natural processes, such as afforestation /reforestation (planting trees) and soil carbon sequestration, to absorb and store CO_2.
- Engineered Solutions use advanced technologies and chemical processes, such as Direct Air Capture (DAC) and carbon mineralization, to remove and durably store CO_2.
- Hybrid Solutions combine aspects of both, often using natural systems to capture the CO_2 (e.g., biomass) and engineered processes to ensure more durable storage.

Nature-based solutions stand out as more cost-effective and viable in the short run, while some technological alternatives have potential to become more relevant later this century. The European Commission recognises the crucial role of CDR and intends to focus on nature-based options.

Examples of CDR include:

- Afforestation/reforestation: transforming non-forested areas into woodland by planting, trees to capture and store CO_2.
- Soil carbon sequestration: natural process where plants convert CO_2 from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration: rewetting and revegetation of degraded peatlands can capture CO_2, with CO_2 stored in soils.
- Biochar: a charcoal-like substance created from plant matter which can store carbon; it can be used on agricultural land (with benefits for the soil and crop yields), or in products.
- Enhanced rock weathering: crushed silicate rock such as basalt can be spread on agricultural land (with benefits for the soil and crop yields) to capture and store CO2.
- Bioenergy with Carbon Capture and Storage (BECCS): biomass (purpose-grown crops or agricultural/forestry residues) captures CO_2 from the atmosphere as it grows; when the biomass is burned to generate electricity or heat, CO_2 is captured and stored.
- Direct Air Carbon Capture and Storage (DACCS): captures CO_2 from the atmosphere using industrial chemical processes and stores it durably in geological storage or products.
- Marine-based techniques such as ocean alkalisation and coastal wetland management: there are a variety of methods that use geochemical or biological capture, and various forms of storage. A subset of CDR methods such as BECCS and DACCS make use of Carbon Capture and Storage (CCS) technologies to deliver net negative emissions (that is, to reduce overall levels of carbon dioxide in the atmosphere) but it is important to note that applying CCS technologies to emissions from fossil fuels can never result in carbon dioxide removal from the atmosphere. Therefore, the terms CDR and CCS are not interchangeable.

AFFORESTATION

Natural terrestrial ecosystems remove atmospheric CO_2 primarily through photosynthesis, transferring carbon from the atmosphere into plant biomass and soils. Forest ecosystems are particularly effective carbon sinks, as trees accumulate carbon in long-lived woody biomass while also enhancing belowground carbon storage through root systems, litter inputs, and soil organic matter formation. Globally, forest ecosystems store a substantial share of

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terrestrial carbon, distributed across aboveground biomass, roots, deadwood, litter, and soils, making them a critical component of the global carbon cycle.

Carbon removal through afforestation occurs mainly via biological carbon sequestration, whereby atmospheric CO_2 is fixed into organic carbon during tree growth. Carbon is initially stored in leaves, stems, and roots and subsequently transferred to soils through litterfall, root turnover, and microbial processing. While forest soils can retain carbon for long periods, the storage of organic carbon is inherently dynamic, as biological decomposition and disturbance processes can return CO_2 to the atmosphere. The long-term effectiveness of afforestation as a carbon removal pathway therefore depends on forest growth rates, species composition, site conditions, and management practices that influence both biomass accumulation and soil carbon stability. The long-term carbon storage also depends on the usage of the wood: while it is possible to store a share of the carbon in timber products (e.g., buildings, furniture), some of the carbon from the leftover parts of the trees that remain in the woods (e.g., branches, stumps) will still be released to the atmosphere.

In the context of carbon removal in terrestrial ecosystems, afforestation refers to the establishment of forest vegetation on land that has not been forested for an extended period, with the dual objective of atmospheric CO_2 removal and ecosystem restoration. Afforestation increases carbon stocks by expanding forest area and initiating new carbon sinks, particularly on degraded, abandoned, or marginal lands. The magnitude and durability of carbon sequestration vary according to climate, soil properties, tree species, and silvicultural management.

Afforestation systems are designed through careful selection of tree species and management regimes to optimize carbon uptake while maintaining ecosystem health. Species choice influences growth rates, carbon allocation patterns, water and nutrient use, and resilience to disturbances. Mixed-species and native-species plantations are increasingly favoured due to their enhanced ecological stability, biodiversity benefits, and reduced vulnerability to pests, diseases, and climate extremes. Forest management practices, including thinning, harvesting, and regeneration strategies, further determine long-term carbon dynamics and the balance between carbon storage in standing biomass and harvested wood products.

Afforestation can serve multiple land-use functions beyond carbon removal. It contributes to land restoration, thus providing areas for education, learning and recreation as well as for physical and mental well-being. It also contributes to soil protection, biodiversity enhancement, and regulation of hydrological cycles, while also supporting timber production and rural development. Carbon stored in harvested wood products may remain sequestered for extended periods when used in long-lived applications (buildings, furniture, etc.), thereby extending the carbon storage function beyond the forest itself. Afforestation may be implemented as continuous forest cover or through staged planting, depending on land availability and management objectives. However, continuous forest cover supports balanced, long-term carbon storage rather than a rapid, short-term increase in carbon stocks.



Figure 1. Plant preparation

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Figure 2. Afforestation planting design

From a classification perspective, afforestation represents a nature-based CDR pathway, distinct from engineered solutions but complementary to them. While afforestation is biologically driven, its effectiveness and permanence are strongly influenced by human planning, management, and governance. Poorly designed afforestation such as monocultures or inappropriate species selection can lead to reduced biodiversity, increased water stress, or heightened disturbance risk, underscoring the need for sustainable implementation (Hasegawa et al. 2024).

Afforestation enables the durable removal of atmospheric CO_2 through biological sequestration in biomass and soils, with storage occurring in terrestrial ecosystems and, indirectly, in long-lived wood products. When carefully planned and integrated into broader land-use and climate strategies, afforestation can provide a scalable and multifunctional carbon removal option that contributes to climate mitigation while supporting ecosystem restoration and sustainable land management (Udawatta et al. 2022).

CURRENT STATE OF AFFORESTATION AS CDR TECHNOLOGY

Afforestation is a well-established land-use practice, but in the context of CDR it continues to require targeted research and development to improve effectiveness, permanence, and integration with climate and land-use policy. Research and development at this stage focuses on refining species selection, site suitability, forest management practices, carbon accounting methodologies, and understanding long-term carbon dynamics in biomass and soils under changing climatic conditions.

At the research and development stage, stability and predictability of policy and financial support remain essential, particularly for long-term ecological studies and modelling efforts. Afforestation projects typically operate over multi-decadal timeframes, meaning that uncertain or short-term funding can undermine research before outcomes become measurable (Li et al. 2025). While afforestation is generally less capital-intensive than engineered CDR technologies, early-stage investments still face risks related to survival rates, growth performance, climate impacts (e.g. drought, fire, pests), and land-use competition.

Risk mitigation and absorption by public institutions is therefore important, especially where afforestation projects are undertaken in marginal or degraded lands or where innovative approaches (e.g. mixed-species stands, climate-adaptive planting) are tested. In addition to direct financial support, broader policy incentives and a supportive political environment are critical to generate early demand, including clear land-use strategies, recognition of afforestation within national climate targets, and alignment with biodiversity and rural development objectives (Strauss et al. 2024).

Afforestation has moved beyond small-scale experimentation and is widely implemented, but demonstration remains critical for validating new approaches, contexts, and management models. In the demonstration stage, the emphasis shifts toward scaling pilot projects, testing afforestation in diverse ecological and socio-

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economic settings, and demonstrating the long-term viability of carbon sequestration under real-world conditions.

At this stage, investments remain risky, as carbon benefits increase slowly and are vulnerable to disturbances such as fire, disease, or land-use change. Continued political and social support is therefore crucial to sustain incentives, ensure landowner participation, and enable early adoption of improved afforestation practices (Jovanelly et al. 2026). Demonstration projects also play a key role in refining monitoring, reporting, and verification (MRV) systems, particularly for biomass growth, soil carbon changes, and permanence risks.

Public support mechanisms at this stage often include grants, co-financing schemes, and technical assistance, helping to bridge the gap between initial planting and the point at which carbon or timber revenues may materialise. Demonstration projects further contribute to social acceptance by showcasing co-benefits such as biodiversity enhancement, erosion control, water regulation, and rural employment as well as provision of areas for physical and recreational activities and nature education.

Afforestation is widely regarded as a mature CDR option, with established knowledge, proven implementation pathways, and a long history of large-scale deployment. In the mature stage, scale becomes the dominant imperative, with the challenge shifting toward mobilising sufficient land, finance, and governance capacity to deliver sustained carbon sequestration at meaningful climate-relevant scales.

For mature afforestation systems, revenue streams must be robust and predictable, combining public and private sources such as timber markets, carbon credits, ecosystem service payments, and rural development funding. As afforestation scales, efficiency gains and improved management practices can lower the cost per unit of carbon sequestered, enhancing its cost-effectiveness compared to alternative CDR options.

Cost-effectiveness is particularly important given the large areas required, and support mechanisms should prioritise afforestation approaches that deliver high carbon permanence and additional environmental benefits, while avoiding negative impacts such as biodiversity loss, water stress, or land-use conflicts. Stability of support remains essential, as forests require long-term management and protection to ensure carbon storage is maintained (Cook-Patton et al 2021).

In the mature stage, incentive mechanisms should increasingly move toward self-sustaining models, where afforestation is embedded within standard land-use planning, forestry markets, and climate policy frameworks. Direct government support can gradually shift toward regulatory certainty, long-term carbon accounting rules, and risk-management instruments, ensuring that afforestation continues to contribute reliably to climate mitigation without permanent reliance on subsidies.

CONCLUSIONS FROM THE C-SINK PROJECT

Afforestation represents a well-established approach to CDR that can contribute meaningfully to climate mitigation objectives when implemented in a sustainable, carefully planned, and well-governed manner. As a nature-based solution, it enables the removal of atmospheric CO_2 through biological sequestration in tree biomass and forest soils, while also generating a wide range of environmental and social benefits.

Afforestation benefits from a high level of technological maturity, underpinned by decades of scientific research, operational experience, and existing policy and management frameworks. Unlike many emerging carbon removal technologies, afforestation can already be deployed at scale using established forestry practices. Its

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long-term effectiveness, however, is highly dependent on context-specific factors, including species selection, site characteristics, forest management regimes, and strategies to ensure the permanence of stored carbon.

Substantial carbon sequestration can be achieved through afforestation, particularly during the active growth phase of forests, with carbon accumulated both aboveground in woody biomass and belowground in roots and soils. Although carbon uptake rates vary widely depending on climate, species composition, and management practices, afforestation can deliver significant cumulative removals over multi-decadal timescales. As forests mature, net carbon uptake typically declines as ecosystems approach equilibrium, highlighting the importance of long-term management decisions, including harvesting practices and the use of harvested wood in long-lived products that can extend carbon storage beyond the forest ecosystem.

In addition to its role in climate mitigation, afforestation provides multiple co-benefits that extend beyond carbon removal. These include ecosystem restoration, enhanced biodiversity, improved soil protection, regulation of water cycles, and increased resilience to climate-related stresses such as erosion and desertification. These broader benefits contribute to the social acceptability of afforestation and support its integration into wider land-use and environmental strategies, particularly when projects focus on native species and degraded or marginal lands.

At the same time, large-scale afforestation faces important constraints and risks. These include competition with other land uses, notably agriculture and urban development, significant land and resource requirements, and long-time horizons before full climate benefits are realised. Carbon permanence is also subject to risks from disturbances such as wildfires, pests, droughts, and inadequate management. Poorly designed afforestation initiatives (such as monoculture plantations or inappropriate species selection) can negatively affect biodiversity, water availability, and ecosystem stability.

Afforestation is therefore most effective when deployed as part of a broader portfolio of CDR strategies rather than as a standalone solution. Integrating afforestation with complementary approaches such as biochar application, artificial soils, bioenergy with carbon capture and storage, and improved soil carbon management can enhance overall carbon removal efficiency, increase durability, and reduce systemic risks. Such integrated deployment can also improve land-use efficiency and create synergies across climate, energy, and circular economy objectives.

Robust Monitoring, Reporting, and Verification (MRV) systems are essential to ensure the credibility and transparency of afforestation-based carbon removals. Accurate quantification of carbon stocks and fluxes in biomass and soils, aligned with internationally recognised methodologies, underpins trust in afforestation as a climate mitigation option. Advances in remote sensing, forest inventories, and digital monitoring technologies play a critical role in supporting large-scale implementation and long-term accountability.

Overall, afforestation can make a substantial contribution to climate mitigation efforts when supported by long-term policy commitment, coherent land-use planning, sustainable forest management, and integration with other carbon removal pathways. Under these conditions, afforestation constitutes a mature, cost-effective, and multifunctional approach capable of delivering durable carbon removal alongside ecosystem restoration and broader societal benefits.

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10.7. Appendix G

Synergies - L1

Actions required to secure the large-scale deployment of the leading CDR approaches to meet EU climate targets

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CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR): SYNERGIES

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, European leaders endorsed the objective of achieving a climate-neutral Europe (EU) by 2050. This followed the commitments made by all European member states that ratified the Paris Agreement in 2015 (United Nations Framework Convention on Climate Change [UNFCCC], 2016). The Agreement is a legally binding international treaty that sets long-term goals to guide all nations to substantially reduce greenhouse gas (GHG) emissions to hold global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

The European Climate Law (European Parliament & Council, 2021) proposed in 2020, as a part of the European Green Deal (European Commission, 2019), the strategy through which to achieve EU climate neutrality by 2050. It legally binds the EU to reduce net greenhouse gas (GHG) emissions. It establishes an intermediate milestone, requiring a reduction in net greenhouse gas emissions of at least 55% by 2030 compared with 1990 levels. To adopt these ambitious climate goals, particularly with its proposed 90% net GHG reduction target for 2040, the implementation of technologies and practices for active carbon dioxide removal (CDR) and durable storage of existing carbon dioxide from the atmosphere and drastic reduction of emissions by switching to renewables and improving energy efficiency. Combining emission reductions with carbon removal is essential because cutting emissions alone is not enough to reverse current atmospheric CO_2 levels, to meet 2050 net-zero and net-negative emission goals.

CDR is primarily needed to offset emissions from hard-to-abate sectors (like cement, aviation, chemicals and steel industry) that cannot be eliminated entirely, and to counter declining natural carbon sinks, making CDR a climate necessity and strategic opportunity for jobs and innovation, supported by EU policies like the Carbon Removals and Carbon Farming (CRCF) Regulation (EU 2024/3012).

This involves developing strategies for both land-based (forests, agriculture) and engineered (Direct Air Capture, Bioenergy with CCS) technologies, setting up certification methodologies for permanent carbon removals activities like the EU's CRCF, and creating incentives through mechanisms like the EU Emissions Trading System (ETS) to scale up CDR as a vital economic opportunity and strategic necessity. The EU ETS is a cornerstone of the Union's climate policy and constitutes its key tool for reducing greenhouse gas emissions in a cost-effective way.

The C-SINK project funded by Horizon Europe aims to establish the foundations to build a standardized and transparent European CDR market to contribute to the implementation of climate change mitigation measurements through the responsible deployment of CDR technologies, by complementing existing EU and international net zero efforts with trustworthy accounting methodologies based on robust Monitoring, Reporting, and Verification (MRV) pre-standards development and environmental policy strategies.

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CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR technologies is an umbrella term for techniques that can be used to capture carbon dioxide (CO_2) from the atmosphere and store durably in geological, terrestrial, or ocean reservoirs, or in products with varying CO_2 storage durations from decades to millennia (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

Land-based CDR technologies are divided into nature-based solutions and engineered solutions, at different technology readiness levels:

- Nature-based solutions leverage natural processes, such as afforestation /reforestation (planting trees) and soil carbon sequestration, to absorb and store CO_2.
- Engineered solutions use advanced technologies and chemical processes, such as Direct Air Capture (DAC) and carbon mineralization, to remove and durably store CO_2.

Nature-based solutions stand out as more cost-effective and viable in the short run, while some novel technological alternatives have potential to become more relevant later this century. The European Commission recognises the crucial role of CDR and intends to prioritize nature-based options, these solutions for climate adaptation, aiming to enhance biodiversity and resilience.

Examples of nature-based CDR include:

- Afforestation/reforestation: transforming non-forested areas into woodland by planting, trees to capture and store CO_2.
- Soil carbon sequestration: natural process where plants convert CO_2 from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration: rewetting and revegetation of degraded peatlands can capture CO_2, with CO_2 stored in soils.

Examples of engineered CDR include:

- Biochar: a charcoal-like substance made by heating plant matter in low-oxygen conditions, allowing carbon to be stored; it can be used on agricultural land (improving soil properties and crop yields) or in products. Enhanced rock weathering: crushed alkaline amafic or ultramafic rock (such as basalt or dunite) can be spread on agricultural land (with benefits for the soil and crop yields) to capture and store CO_2.
- Bioenergy with Carbon Capture and Storage (BECCS): biomass (purpose-grown crops or agricultural/forestry residues) captures CO_2 from the atmosphere as it grows; when the biomass is burned to generate electricity or heat, CO_2 is captured and stored in geological reservoirs.
- Direct Air Carbon Capture and Storage (DACCS): captures CO_2 from the atmosphere using industrial chemical processes and stores it durably in geological storage or products.

A subset of CDR methods such as BECCS and DACCS make use of Carbon Capture and Storage (CCS) technologies to deliver net negative emissions (that is, to reduce overall levels of carbon dioxide in the atmosphere) but it is important to note that applying CCS technologies to emissions from fossil fuels can never result in carbon dioxide removal from the atmosphere. Therefore, the terms CDR and CCS are not interchangeable. In the context of C-SINK project, emissions of the technology deployed have been calculated, Therefore, using geological reservoirs for CCS in the active oil and gas sector an approach to minimize their emissions.

SYNERGIES AMONG CDR TECHNOLOGIES

Carbon dioxide removal encompasses a set of anthropogenic activities that extract CO_2 directly from the atmosphere and store it in

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a safe and permanent manner. Given the scale and urgency of climate mitigation required to meet the objectives of the Paris Agreement, there is growing consensus that emission reductions alone are insufficient and must be complemented by substantial and sustained CDR deployment. However, individual CDR technologies exhibit inherent limitations related to scalability, permanence, cost, and environmental trade-offs, necessitating a systems-based approach that integrates multiple complementary pathways.

Natural and managed ecosystems already play a central role in the global carbon cycle, with soil and vegetation constituting major active carbon reservoirs. Soils alone store carbon stocks that exceed those of the atmosphere, in both organic and inorganic forms. Biological carbon fixation through photosynthesis and microbial processes transfer atmospheric CO_2 into organic matter, while geochemical processes such as carbonation and silicate weathering convert CO_2 into inorganic carbon forms with significantly longer residence times. Despite their importance, these processes are constrained by biological turnover, environmental variability, and slow reaction kinetics, limiting their capacity to deliver durable carbon removal at climate-relevant timescales when deployed in isolation.

Due to the novelty or many CDR technologies, synergies or co-deployments are currently overlooked. Synergies among CDR technologies are necessary to overcome constraints and maximize effectiveness by combining biological, geochemical, and engineered processes in a way which benefits each individual approach by co-deployment. However, poorly designed integrated CDR systems risk causing biodiversity loss, soil degradation, and water stress, undermining both climate and environmental objectives. These risks are amplified under large-scale deployment, particularly when afforestation, biomass harvesting, and BECCS are combined, increasing pressure on land, water, and nutrient resources.

Synergistic effects act similar to catalysts in chemical systems, they enhance system efficiency without requiring additional material input. An example can be found in the co-deployment of afforestation coupled with biochar production and BECCS, in which afforestation provides the biomass input for biochar production and BECCS, while the ash waste from BECCS increases biochar production, and biochar deployment increases the biomass output from afforestation. Synergies are enabled through the combined deployment of these technologies within an integrated framework which would not be possible if used in isolation. Another example is artificial soils combined with enhanced weathering and microbial carbon fixation to enhance net carbon removal, improve storage permanence, and increase overall system resilience (Smith et al. 2024). These synergies operate by redistributing carbon across multiple reservoirs, reducing dependence on any single storage pathway and mitigating reversal risks associated with biological carbon pools.

Artificial soils (Technosols) exemplify the potential of integrated CDR systems. Engineered from organic and inorganic residual materials, artificial soils can be designed to optimize physical structure, nutrient availability, and chemical conditions conducive to carbon stabilization. When deployed within synergistic CDR systems, artificial soils enable simultaneous accumulation of soil organic carbon through plant and microbial activity and inorganic carbon through mineral carbonation and weathering processes. The incorporation of biochar further enhances carbon persistence by increasing resistance to microbial decomposition and improving soil aggregation, while alkaline mineral amendments promote long-term inorganic carbon sequestration. This synergy is being

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tested at an active mine site in Spain as part of the C-SINK project.

Beyond soil-based systems, synergistic CDR approaches facilitate coupling between land-use and energy systems. Biomass produced through afforestation or soil restoration can supply feedstocks for bioenergy with carbon capture and storage (BECCS) or biochar production, enabling partial transfer of biogenic carbon into geological storage or long-lived soil reservoirs. Enhanced weathering complements these pathways by accelerating natural CO_2 uptake through mineral dissolution, resulting in dissolved bicarbonates or carbonate mineral formation. Collectively, these interactions shift carbon from short-lived biological cycles toward longer-lived geological and geochemical sinks.

Despite being promising, synergistic CDR systems remain at an early stage of development. Key challenges include heterogeneity in technology readiness levels across component technologies, limited empirical data on integrated system performance, and the absence of standardized monitoring, reporting, and verification (MRV) frameworks capable of accounting for complex carbon fluxes across multiple pathways. Additional constraints arise from land-use competition, resource availability, energy requirements, and potential environmental trade-offs, all of which must be addressed through careful system design and governance.

The C-SINK project suggests that the effective implementation of CDR synergies requires a phased approach, starting with targeted pilot and demonstration projects designed to generate robust empirical evidence under diverse environmental and socio-economic conditions. These efforts must be supported by integrated MRV methodologies, long-term policy stability, and cross-sectoral coordination across land-use, energy, waste, and climate policy domains. Advances in data collection, modelling, and decision-support tools including the application of artificial intelligence and machine learning will be critical to optimizing system performance and informing large-scale deployment strategies (Cobo et al., 2023).

In conclusion, synergistic deployment of CDR technologies offers potentially long-term viable pathway to achieving durable, scalable, and resilient carbon removal consistent with EU climate neutrality objectives. By integrating biological uptake, soil processes, geochemical stabilization, and engineered storage within coherent system-level frameworks, CDR synergies can substantially enhance net carbon removal while delivering co-benefits for ecosystem restoration, resource efficiency, and sustainable land management.

CURRENT STATE OF THE SYNERGIES AMONG LEADING CDR TECHNOLOGIES

Synergies among CDR technologies are currently predominantly in the research and development (R&D) stage. While individual CDR approaches such as afforestation, biochar, BECCS, enhanced weathering, artificial soils, and microbial CO_2 fixation are being studied on their own, their combined deployment remains an emerging and underexplored field. Furthermore, some CDR approaches e.g. afforestation and bioenergy systems, are relatively well established- However, other CDR technologies including artificial soils and microbial carbon fixation remain at lower technology readiness levels.

As highlighted in the C-SINK project, available scientific literature on multi-CDR integration is limited, fragmented, and often qualitative, necessitating structured research efforts to systematically identify, classify, and evaluate synergistic interactions.

At this stage, stable and predictable policy and financial support are particularly important, as synergy-oriented research is

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inherently interdisciplinary and long-term. Understanding how different CDR technologies interact requires coordinated experimentation across land use, energy systems, material supply-chains, and biogeochemical cycles. Many synergistic effects (such as soil carbon stabilization and enhancement through biochar-artificial soil-enhanced rock weathering combinations or optimized biomass use linking afforestation with BECCS) only become evident over extended temporal and spatial scales. Short or uncertain funding cycles risk leaving these interactions insufficiently understood and prevent the development of robust baselines for additionality and accounting, as well as high risks on leakage and reversal.

Uncertainty is especially pronounced in this stage, as combining technologies introduces compound risks related to performance, carbon accounting, permanence, and monitoring. As a result, public-sector risk absorption and coordination are essential to enable early-stage research. Beyond financial instruments, broader policy recognition of CDR synergies, rather than isolated technologies, is necessary to create a supportive political environment that promotes integrated approaches and encourages collaboration across traditionally separated sectors.

CDR synergies move into the demonstration stage when integrated combinations of technologies are tested in pilot and pre-commercial settings, such as biochar application in afforestation systems, enhanced weathering integrated into artificial soils, or biomass value chains linking afforestation, biochar production, and BECCS. At this stage, scale becomes important, but investments remain risky because the combined performance of these technologies has not yet been fully validated under real-world conditions.

Demonstration projects are essential for generating empirical data on how synergistic CDR systems perform in practice, including their net carbon removal, operational feasibility, environmental co-benefits, and potential trade-offs. They also play a critical role in advancing Monitoring, Reporting, and Verification (MRV) methodologies capable of capturing interactions between multiple CDR approaches within a single project. The C-SINK analysis highlights that current MRV frameworks are largely designed for single-technology applications, making demonstration projects vital for testing integrated accounting approaches and defining credible baselines.

At this stage, political and social support becomes particularly important. Synergistic CDR projects often span multiple regulatory domains, such as land use, waste management, energy, and climate policy, creating institutional complexity and potential permitting barriers. Continuous high integrity and transparency research is necessary to increase public support, targeted incentives, and stakeholder engagement, which are required to ensure early adoption, maintain investor confidence, and build societal acceptance. Demonstration projects have a learning function, helping to identify which technology combinations are most robust, scalable, and context appropriate.

In a more mature stage, synergies among CDR technologies would be systematically integrated into climate mitigation strategies, with scale becoming the dominant imperative. Rather than deploying individual CDR approaches in isolation, mature deployment would prioritise optimized portfolios of technologies that maximise carbon removal, resource efficiency, and co-benefits while minimising costs and risks. In this stage, synergies will no longer be experimental but will represent standardised and repeatable deployment methods.

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For maturity to be achieved, revenue streams must be stable, sufficient, and aligned across interacting technologies. This is particularly important for synergistic systems, where the performance and economic viability of one component may depend on another (e.g. biomass supply chains linking afforestation, biochar, and BECCS). Revenue is likely to come from a combination of public and private sources, including carbon markets, energy markets, land restoration funding, and circular economy mechanisms. As integrated systems scale up, learning effects and operational optimisation can reduce per-unit costs, improving overall cost-effectiveness compared to standalone CDR approaches (Adun et al., 2024).

Cost-effectiveness is particularly important in the mature stage, given the large scale of carbon removal required to meet EU climate targets. However, supporting mechanisms should not solely focus on cost minimization; they must also consider broader benefits and potential risks, such as biodiversity impacts, land-use competition, and social acceptance. Stability remains a defining feature of effective support: synergistic CDR systems require long-term regulatory certainty, durable incentive mechanisms, and coherent policy frameworks across sectors.

Over time, CDR synergies will be integrated into standard land management, energy production, and industrial practices. In this context, the role of public policy shifts from direct subsidies toward enabling coordination, ensuring MRV integrity, and providing long-term certainty, allowing synergistic carbon removal systems to contribute reliably and at scale to Europe's net-zero objectives.

SCALE UP BARRIERS ON CDR TECHNOLOGIES SYNERGIES

One of the primary barriers to large-scale deployment is the uneven maturity and scalability of individual CDR technologies. While some approaches, such as afforestation and bioenergy systems, are relatively well established, others (including artificial soils and microbial carbon fixation) remain at lower technology readiness levels. When combined, these differences in maturity can amplify uncertainty, particularly in relation to long-term performance, carbon permanence, and operational reliability. In addition, integrated systems often involve higher complexity, as underperformance or failure in one component can compromise the effectiveness of the entire system.

Land-use competition and ecological risks represent another major constraint. Large-scale deployment of integrated CDR systems can increase pressure on land, water, and nutrient resources, particularly when afforestation, biomass harvesting, and BECCS are combined. Poorly designed systems risk biodiversity loss, soil degradation, and water stress, undermining both climate and environmental objectives. These risks are compounded by climate-related disturbances such as droughts, wildfires, and pests, which threaten the permanence of land-based carbon storage.

Economic and infrastructural barriers further limit large-scale implementation. High upfront investment costs, especially for BECCS infrastructure and energy-intensive processes such as enhanced weathering, pose significant challenges. Without access to low-carbon energy sources, these technologies risk reduced net climate benefits. In addition, transport requirements for biomass and mineral materials can increase costs and emissions, reducing overall efficiency if not carefully managed.

CONCLUSIONS FROM C-SINK PROJECT

The large-scale deployment of CDR technologies is essential for achieving the European Union's climate neutrality objectives. However, the analysis conducted within the C-SINK project clearly

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demonstrates that no single CDR technology can deliver the required level of removals on its own. Instead, the effective contribution of CDR to EU climate targets depends on the strategic integration of multiple, complementary technologies, deployed in synergistic combinations that enhance carbon removal efficiency, permanence, and co-benefits while reducing systemic risks.

Integrated CDR deployment offers significant advantages, including improved land-use efficiency, enhanced ecosystem services, and greater resilience against technological, environmental, and market uncertainties. Synergies between approaches such as afforestation, biochar, BECCS, artificial soils, enhanced weathering, and microbial carbon fixation can increase overall carbon sequestration potential while enabling circular use of biomass, waste materials, and energy streams. Nevertheless, translating these synergies from conceptual frameworks into large-scale implementation presents substantial technological, operational, and governance challenges.

A critical cross-cutting challenge is the lack of robust, integrated Monitoring, Reporting, and Verification (MRV) frameworks. Existing MRV systems are largely designed for single-technology projects and are insufficient to capture the complex carbon pathways, interactions, and additionality associated with multi-CDR systems. Uncertainty around baselines, accounting boundaries, and long-term liability remains a major obstacle to market integration, regulatory approval, and investor confidence.

To overcome scale-up barriers, the C-SINK analysis highlights the need for a phased and coordinated approach to implementation, beginning with targeted pilot and demonstration projects. Real-world testing of the most promising CDR synergies is essential to generate empirical data on carbon removal efficiency, resource requirements, environmental impacts, and operational feasibility. Pilot projects conducted across diverse geographical and climatic contexts can help identify best practices, reveal unforeseen challenges, and support adaptive management before large-scale roll-out.

Equally important is the development of coherent policy and regulatory frameworks that explicitly recognise and support integrated CDR deployment. Large-scale implementation will require alignment across land-use planning, energy policy, waste management, and climate regulation. Stable and predictable policy signals, combined with financial incentives such as carbon credits, public–private partnerships, and innovation funding, are necessary to reduce investment risk and enable early market formation. Over time, these mechanisms should evolve toward durable, market-based systems capable of sustaining deployment at scale.

The analysis further underscores the importance of advanced data collection, modelling, and decision-support tools. Extensive field data, combined with numerical modelling and emerging approaches such as artificial intelligence and machine learning, can improve the assessment and optimisation of CDR synergies. These tools are critical for informing policy decisions, improving cost-effectiveness, and ensuring environmental integrity as deployment scales.

Ultimately, the successful large-scale deployment of integrated CDR technologies depends on moving beyond isolated interventions toward system-level solutions embedded within standard land management, energy production, and industrial practices. By addressing technological and operational barriers through coordinated planning, robust MRV, sustained policy support, and continuous learning, synergistic CDR systems can evolve from experimental concepts into reliable

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pillars of Europe's long-term climate mitigation strategy.

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10.8. Appendix H

MCO_2 - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

MICROBIAL CO_2 FIXATION (MCO_2)

REVOLUTIONIZING AGRICULTURE: HARNESSING MICROBIAL POWER FOR CARBON REMOVAL

As the world grapples with the urgent challenge of climate change, two primary strategies emerge: the crucial reduction of emissions at their source, and the increasingly vital removal of existing CO_2 from the atmosphere. This second strategy, known as Carbon Dioxide Removal (CDR), is gaining traction through a range of innovative technologies. This paper highlights one of the most promising and natural solutions: Microbial CO_2 Fixation (MCO_2).

WHAT IS MCO_2?

Microbial CO_2 Fixation (MCO_2) is a nature-positive technology that leverages the innate power of microorganisms to capture atmospheric CO_2 and convert it into liquid and solid organic and inorganic carbon compounds within the soil. While plants fix CO_2 through photosynthesis, a vast and often untapped potential lies in the soil's microbiome. Certain microorganisms utilize specialized biochemical pathways to draw down carbon, effectively acting as a natural carbon sink (Berg, 2011). Advanced microbial biostimulants (such as ekofertile® plant and microfertile® plant) are designed to enhance this very process, turning agricultural land into a powerful engine for carbon sequestration while simultaneously boosting crop health and yield.

HOW DOES THE MCO_2 PROCESS WORK?

The MCO_2 process begins with the production of powerful microbial bio–stimulants. Using eco-friendly methods like bioleaching (e.g., InnoBioTech®), we accelerate the breakdown of natural minerals, transforming them into a rich, bioavailable nutrient solution. This process not only solubilizes essential minerals but also cultivates a diverse consortium of beneficial microorganisms and their metabolites.

The resulting biostimulant is a potent soil activity enhancer. Once transported to farmers and applied via spraying, it revitalises the soil ecosystem. The introduced microbes enhance nutrient availability, stimulate plant growth, and, most importantly, drive the process of capturing atmospheric CO_2 and converting it into long-lasting soil organic and inorganic carbon.



WHAT IS THE CARBON SEQUESTRATION POTENTIAL OF MCO_2?

The capacity of soil microbes to fix carbon is significant and measurable. Research indicates that heterotrophic CO_2 fixation in soils can range from 2.8 to 36.5 mg CO_2/m² per hour, depending on soil conditions such as pH (Šantrůčková et al., 2005). According to the IPCC1, once captured through soil carbon sequestration practices, carbon can be stored for timeframes ranging from decades to centuries, making MCO_2 a durable CDR solution. By actively managing and amplifying the soil microbiome, we can significantly accelerate and maximize this natural carbon removal process.

WHAT IS THE ECONOMIC VALUE FOR FARMERS?

MCO_2 is not just an environmental solution; it's an economic opportunity. With an estimated cost of ~€1.10 per litre and application rates of 10-200 litres per hectare, this technology is highly accessible.

The return on investment is compelling:

- Substantial Cost-Benefit: Farmers can see a return up to 10 times higher compared to conventional inputs.
- Reduced Input Costs: Cuts the need for agrochemicals by up to 50%.

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- New Revenue Streams: Potential to earn €30–300 per hectare in carbon credits.
- Enhanced Yield & Resilience: Leads to healthier crops, higher yields, and improved drought and disease resistance.

WHAT ARE THE ADDITIONAL CO-BENEFITS?

The advantages of implementing MCO_2 extend far beyond carbon capture:

For Farmers:

- Increased sugar and protein content in crops.
- Faster crop development and higher yields.
- Enhanced resistance to disease and drought.
- Improved efficiency of agrochemicals.

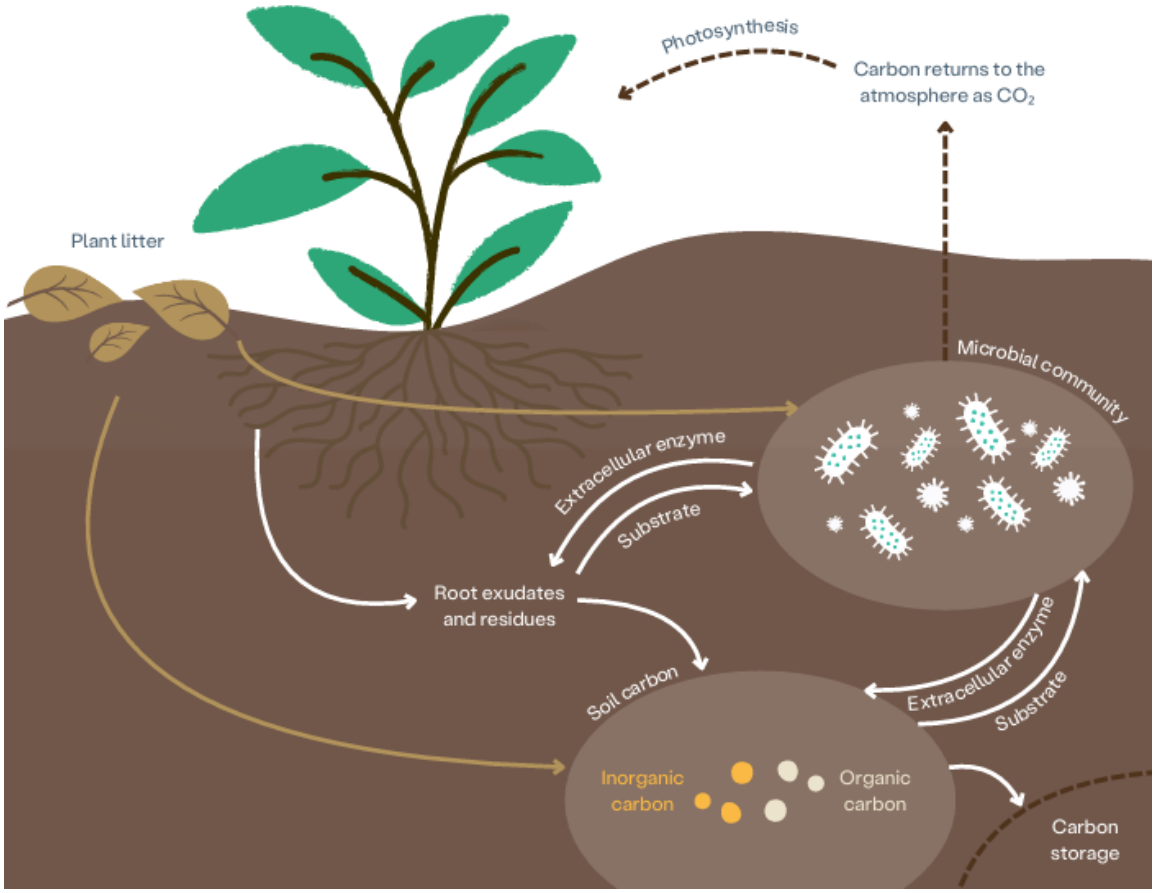
For the Mining Sector:

- Provides a new, ecological processing pathway (bioleaching) to increase the value and purity of mineral products.

These positive effects are measurable and verified, contingent on the correct application of the biostimulant. The primary consideration for implementation is water management, as the process requires adequate water for application.

PIONEERING THE FUTURE: THE C-SINK PROJECT

C-SINK is an EU-funded initiative at the forefront of building a standardized and transparent European market for Carbon Dioxide Removal. As part of this mission, the project is conducting real-world case studies on farmlands across Germany, Slovakia, and Croatia. These sites, with their varied climates and soil types, are being inoculated with diverse microbial consortia (up to 1000 species) produced via bioleaching. The goal is to rigorously quantify and optimize the mechanisms of soil carbon sequestration through MCO_2.



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10.9. Appendix I

BECCS - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

With the aim of neutralizing the worrying increase in atmospheric CO_2 concentration, two possible strategies are being considered. The first, well-known, is the reduction of emissions; the second, much less well-known, is the removal of CO_2 from the atmosphere. Several techniques, known by the acronym CDR (Carbon Dioxide Removal), have been developed for this second strategy. This report will explain one of them: the BioEnergy with Carbon Capture and Storage (BECCS).

BECCS is based on the use of biomass (agricultural residues, forestry products, or dedicated energy crops) to produce energy (heat or electricity) by direct combustion or by converting them into fuels (biodiesel or bioethanol). Biomass consists of organic substances that plants synthesize from water and atmospheric CO_2 during photosynthesis. This CO_2 removed from the atmosphere, is later released as gas when the biomass is burned to produce energy. However, BECCS includes a system to capture and store this gas in a geological sink. In this way, BECSS constitutes a system that combines the production of energy with the removal, capture, and storage of atmospheric CO_2.

BECCS VALUE CHAIN

The BECCS value chain comprises 4 main stages (Fajardy, 2022):

1. Biomass production: Refers to either the primary product, such as dedicated energy crops or harvested wood from forestry, or a by-product, such as forestry residues, agricultural residues, municipal solid waste, industrial waste wood, or manure.
2. Biomass processing and transport: Biomass often requires treatment or densification to meet the quality and format requirements of the chosen conversion pathway.
3. Biomass conversion: Includes a range of processes such as power generation, hydrogen production, biodiesel, and bioethanol production, as well as various industrial applications.
4. Capture, transport, and geological storage: CO_2 is captured using several available technologies, including post-combustion capture (from exhaust gases in air-fired biomass combustion), oxy-combustion (burning biomass in pure oxygen), or pre-combustion capture (as in biomass gasification). The captured CO_2 is then compressed, transported by pipeline or ship, and injected into suitable geological reservoirs for permanent storage.

BECCS STATE OF THE ART

According to the Global CCS Institute (GCCSI, 2023), there are currently two operational BECCS facilities in the United States: Archer Daniels Midland (ADM) Illinois Industrial, which produces ethanol and has a theoretical capture capacity of 1 million tonnes per annum (Mtpa); and Red Trail Energy Richardton Ethanol, with a capacity of 0.18 Mtpa. In addition, more than 40 advanced BECCS projects are registered in North America.

In Europe, two projects stand out: Drax in the United Kingdom and Stockholm Exergi in Sweden. Drax aims to capture 8 Mt of CO_2 each year by 2027 and eventually become carbon-negative by 2030, with a long-term ambition of delivering 16 Mtpa of negative emissions. Nonetheless, the development of BECCS at Drax is currently uncertain. Drax continues to consider the project, but it requires the appropriate support from the UK Government. Stockholm Exergi plans to capture and permanently store 0.8 Mt of CO_2 per year by 2027. In both cases, the captured CO_2 will be transported and stored in geological formations beneath the North Sea.

Other notable European projects include the Hafslund Oslo Celsio Waste-to-Energy Plant in Norway and the Shell Energy and Chemicals Park Rotterdam in the Netherlands, both designed to capture around 0.4 Mtpa of CO_2; Denmark's Amager Bakke Waste-to-Energy facility with a planned capacity of 0.5 Mtpa; and the Bioeléctrica

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de Garray biomass power station in Spain, designed to generate approximately 100,000 MWh annually, avoiding around 24,100 tonnes of CO_2 emissions. Garray was the first facility in Europe to implement CO_2 capture in its biomass combustion plant.

Retrofitting just 38% of existing biomass installations with BECCS would already enable the EU to reach its 2040 target. Expanding implementation to 50% of current facilities could yield around 105 Mt CO_2/yr of durable removals. These figures illustrate that Europe's industrial carbon removal ambition is technically within reach, provided enabling conditions are established.

HOW MUCH CO_2 CAN IT CAPTURE?

Approximately 2 million tonnes of CO_2 from biomass are captured worldwide each year, mainly through bioethanol production. However, estimates suggest that 2–4 billion tonnes of CO_2 (gigatonnes) could be removed annually if BECCS is deployed sustainably. In practice, real-world BECCS systems are expected to achieve removal efficiencies of around 65-85% depending on the capture process, transport logistics, and the overall supply chain.

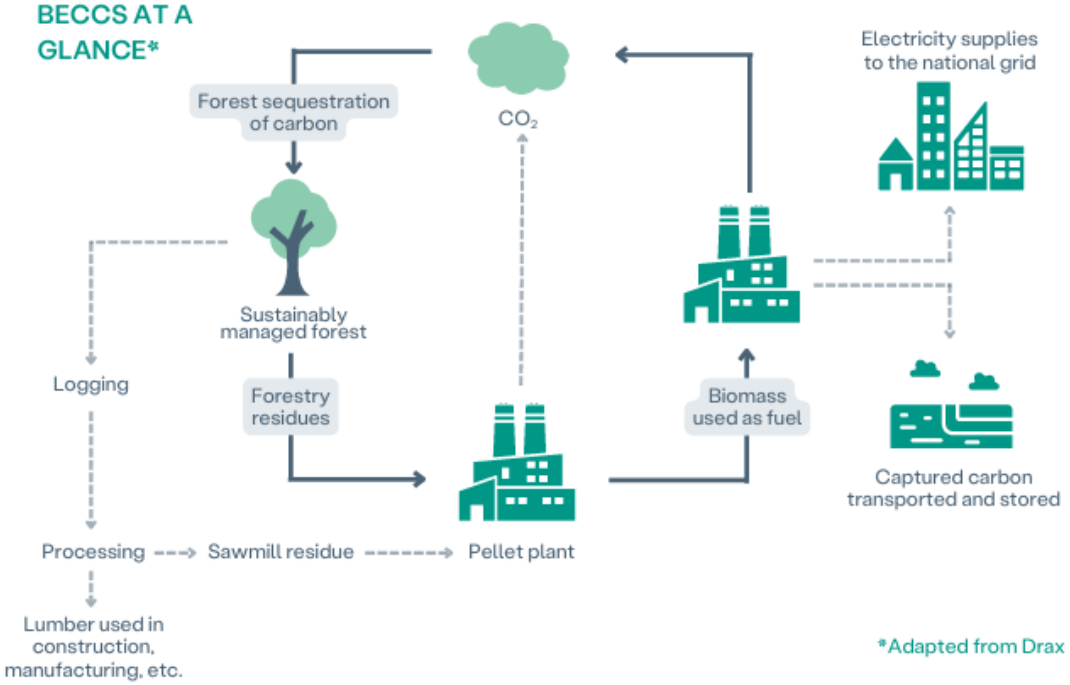
HOW MUCH DOES IT COST?

The cost of implementing BECCS varies considerably due to differences in the underlying capture and storage processes. According to various estimates, the cost of avoiding 1 tonne of CO_2 spans from about US$15 to US$400, depending on the industrial or energy sector (Global CCS Institute, 2019; Samaniego et al., 2023). Research by Fajardy et al. (2021) suggests that BECCS could serve as a technological "safety net" at carbon prices of around US$240 per tonne of CO_2.

C-SINK PROJECT

C-SINK is an EU-funded project that aims to establish the foundations for a standardized and transparent European Carbon Dioxide Removal (CDR) market.

BECCS AT A GLANCE*



*Adapted from Drax

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11.1. Appendix J

ERW - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

ENHANCED ROCK WEATHERING (ERW)

To neutralize the worrying increase in CO_2 concentration in the atmosphere, two possible strategies are being deployed: the first, well-known, is the reduction of emissions; the second, less well-known, is the removal of CO_2 from the atmosphere. Several techniques, known by the acronym CDR (Carbon Dioxide Removal), have been developed for this second strategy. This report is focusing on one of them: Enhanced Rock Weathering (ERW).

Weathering is the combination of the processes of in situ physical disintegration and chemical decomposition of rocks due to the effects of the atmosphere, hydrosphere, and biosphere. Weathering, which affects all types of rock, can in some cases involve CO_2 in chemical reactions that ultimately lead to the formation of new minerals, namely carbonates. In this way, part of the CO_2 is effectively and permanently removed from the atmosphere to form new stable minerals. In fact, the large deposits of carbonate rocks existing on the Earth represent the capture and sequestration of atmospheric CO_2 over geological time.

HOW DOES IT OCCUR?

Atmospheric CO_2 dissolves in water (rainwater, soil moisture, etc.), forming a weak acid (carbonic acid or H_2CO_3), which reacts with minerals, releasing cations, resulting in an increase in alkalinity in solution to form bicarbonate and new carbonate minerals.

To accelerate this process, rocks must be fine-grained and transported to specific locations where they can be dispersed to react with the CO_2-containing water. As grinding and transport involve the use of energy and the related emission of CO_2, it is advantageous to use mining waste that already has the appropriate grain size.

Among the possible places where these ground rocks could be dispersed, agricultural soils stand out, since ERW offers the dual benefit of capturing CO_2 and providing nutrients that improve crop yields. Another place can be the seashore, where ERW benefits from wave action for faster dissolution. ERW can also occur on a mine site where the waste material is stored.

WHAT TYPE OF ROCK?

As rocks are aggregates of one or more minerals, the correct question should refer to what types of minerals can be dissolved by carbonic acid and how fast is the reaction process. Studies have demonstrated that silicate minerals containing high concentrations of Ca, Mg, and Fe, are more prone to release cations that can co-precipitate with CO_2 to form carbonated minerals. The most notable minerals are olivine, pyroxene, and amphibole, which are abundant in rocks such as dunite and basalt. The most outstanding is olivine, as it is the most abundant and fast-weathering magnesium silicate mineral on Earth (Smet et al., 2021; Bullock et al., 2023). This means that olivine-rich rocks have the highest potential for carbon dioxide removal.

HOW MUCH CO_2 CAN IT CAPTURE?

The yield of ERW depends on several parameters such as the type of rock, grain size, climate conditions, and soil properties.

Igneous rocks containing olivine and other Ca-,Fe-, or Mg-bearing silicate minerals have strong CDR potential (0.5–2 Gt CO_2 year by 2050, Beerling et al., 2025), and containing at the same time a range of nutrients (e.g., Na, K, and P) released into solution, making them excellent natural fertilizers.

The reactive surface area of the CDR rock material is increased by reducing the grain size, therefore increasing the speed of weathering (Beerling et al., 2020; Smet et al., 2021).

According to Renforth (2012) and Smet et al. (2021), high temperatures accelerate the weathering process, and intense rainfall is crucial since water is necessary for the chemical reactions to



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take place. Therefore, tropical climates are the most suitable.

Finally, chemical, physical, and biological soil properties have a great influence on the ERW efficiency, since microorganisms boost the physical and chemical breakdown of silicate grains in the soil (Vandeginste et al., 2024).

HOW LONG DOES IT TAKE?

Carbonation rates range from a few months to a few decades (Strefler et al., 2018; Beerling et al., 2020). Some authors, such as Hangx & Spiers (2009), estimated a timeframe of 23 years for the full dissolution of 10 µm olivine particles on beaches. This duration increases to 233 years for a grain size of 100 µm.

HOW MUCH DOES IT COST?

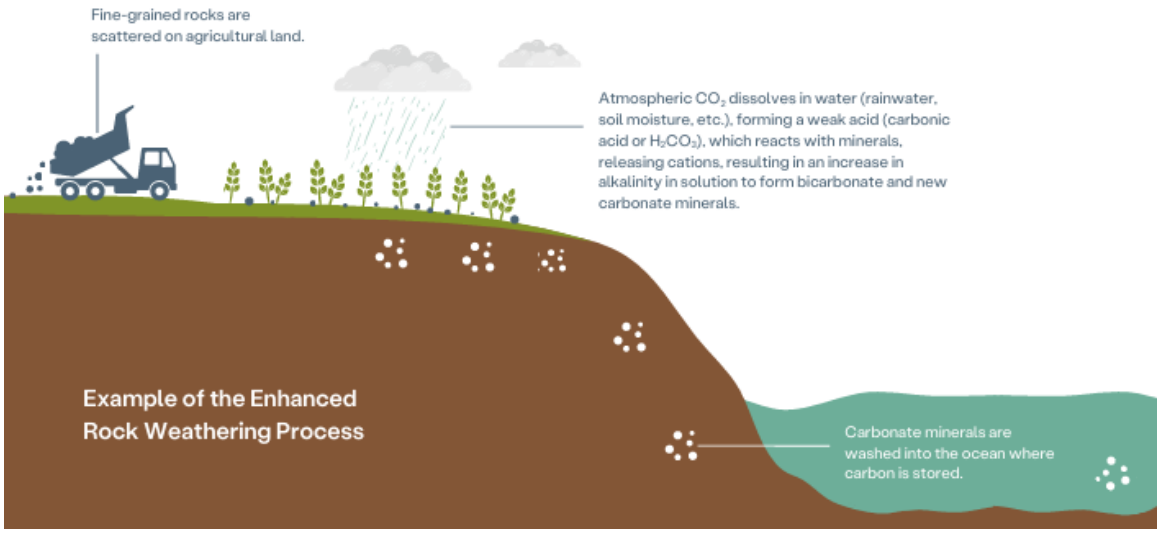
Different economic cost assessments have been carried out with variable results. The costs for ERW are site-specific and affected by factors such as sourcing the feedstock, additional pre-processing steps and transportation distances, and operational expenditure savings such as improved waste management and reduced fertilisers costs. For example, a recent study suggested Monitoring, Reporting & Verification (MRV) costs per tonne of carbon in agricultural deployments ranging from £25 to £425 (mean ~£150) using Frontier data, and from £5 to £95 (mean ~£40) using Grantham Research Institute data (Mercer et al., 2024). CO2RE and ERM research estimated that the cost of deploying ERW in the UK would be £350-864/tCO_2 captured (mean £487/tCO_2) in 2030, and £262-670/tCO_2 captured (mean £365/tCO_2) in 2050 for gross removals (Whitehead, 2025). Costs in a full life cycle are likely to be close to those of other CDR technologies, such as biochar, and lower than expected costs for energy-intensive processes such as direct air capture.

REGULATORY LANDSCAPE

Enhanced rock weathering is being considered by the EU Expert Group on Carbon Removals and Carbon Farming (CRCF) for its inclusion as a CDR method in the Regulation (EU 2024/3012). A certification methodology to allow ERW to generate carbon removal units may be adopted in the future (ICF, Cerulogy, and Ecodiversity, 2025). The Commission is set to assess in 2026 the potential inclusion of carbon removals with permanent storage in the EU Emission Trading Scheme (ETS).

C-SINK PROJECT

C-SINK is an EU-funded project that aims to establish the foundations for a standardized and transparent European Carbon Dioxide Removal (CDR) market. For ERW, C-SINK is developing two distinct field trials in Spain (David mine) and Finland (Kevitsa mine), where MRV is carried out in situ within active mine sites. Both trials test MRV under real, open-system conditions, focusing on transparent, scalable, and long-term sustainable removals through atmospheric CO_2 conversion into permanently stable carbonate forms.



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11.2. Appendix K

BC - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

BIOCHAR (BC)

TURNING BIOMASS INTO A CARBON SINK

One of the most promising CO_2 removal technologies from the atmosphere is biochar (IPCC, 2022), a carbon-rich material produced by heating biomass in the absence of oxygen. This process, called pyrolysis, locks carbon into a stable solid form that can remain in soils for centuries or even millennia (Lehmann & Joseph, 2012).

HOW DOES BIOCHAR WORK?

The process begins with biomass-crop residues, forestry waste, manure, or sewage sludge. Instead of decomposing and releasing CO_2 back into the atmosphere, this biomass is heated to temperatures above 400 °C in low-oxygen conditions. The result is a combination of three products: Biochar (solid carbon), Bio-oil (liquid fuel), and Pyrolysis gas (combustible gas) (Lehmann & Joseph, 2012).

The biochar co-product is the key to carbon removal. Because of its chemical structure, much of the carbon in biochar is highly resistant to chemical and microbial breakdown, moving carbon from the short-lived biosphere into the long-lived geosphere (Chiaramonti et al., 2024; Sanei et al., 2024).

Biochar is similar to charcoal, which is made from wood primarily for fuel. However, biochar is defined not solely on its renewable feedstock basis and production process, but also by its end application. It can be used for environmental management purposes, such as soil amendments, filtration application, or as an additive in other products (e.g. cement and/or steel). Thus, for it to be labelled biochar, the material must be used in applications which ensure long-term stability (i.e. no combustion) (Hagemann et al., 2018).

HOW MUCH CARBON CAN BIOCHAR STORE?

Recent studies estimate that biochar could remove up to 245 million tonnes of CO_2 per year in Europe alone, corresponding to an annual biochar production of around 121 million tonnes (Lefebvre et al., 2023). The permanence of biochar depends on its production conditions and feedstock: higher temperatures showed higher stable carbon in produced biochar (Azzi et al., 2024).

To measure permanence, scientists use methods such as chemical oxidation, incubation experiments, and advanced modelling (Adhikari et al., 2024). These approaches help ensure that carbon credits associated with biochar carbon removal are based on solid science.

WHAT IS THE ECONOMIC VALUE?

The cost and therefore the price of biochar, which is sustainably produced, vary widely depending on feedstock and technology (Trapero et al., 2025). When expressed as cost per ton of CO_2 removed, biochar is very competitive with other engineered CDR methods. As a result of the relatively low cost and the technology readiness and availability, biochar projects already dominate the voluntary carbon market, delivering over 90% of issued CDR credits in 2023 (Smith et al., 2023, CDR.fyi, 2025).

For farmers, biochar offers co-benefits: improved soil health and protection, enhanced water retention (Gholamahmadi et al., 2023; Wei et al., 2023), higher yields (Ye et al., 2020), and reduced need for fertilisers due to improved nutrient retention (Buss et al., 2020). All this means that biochar can generate climate, environmental, and economic value.

WHAT ARE OTHER CO-BENEFITS?



Other co-benefits cover the use of biochar in construction materials such as concrete (Lin et al., 2023) and/or steel industry (Ren et al., 2025) which lead to reducing CO_2 emissions.

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WHAT ARE THE RISKS?

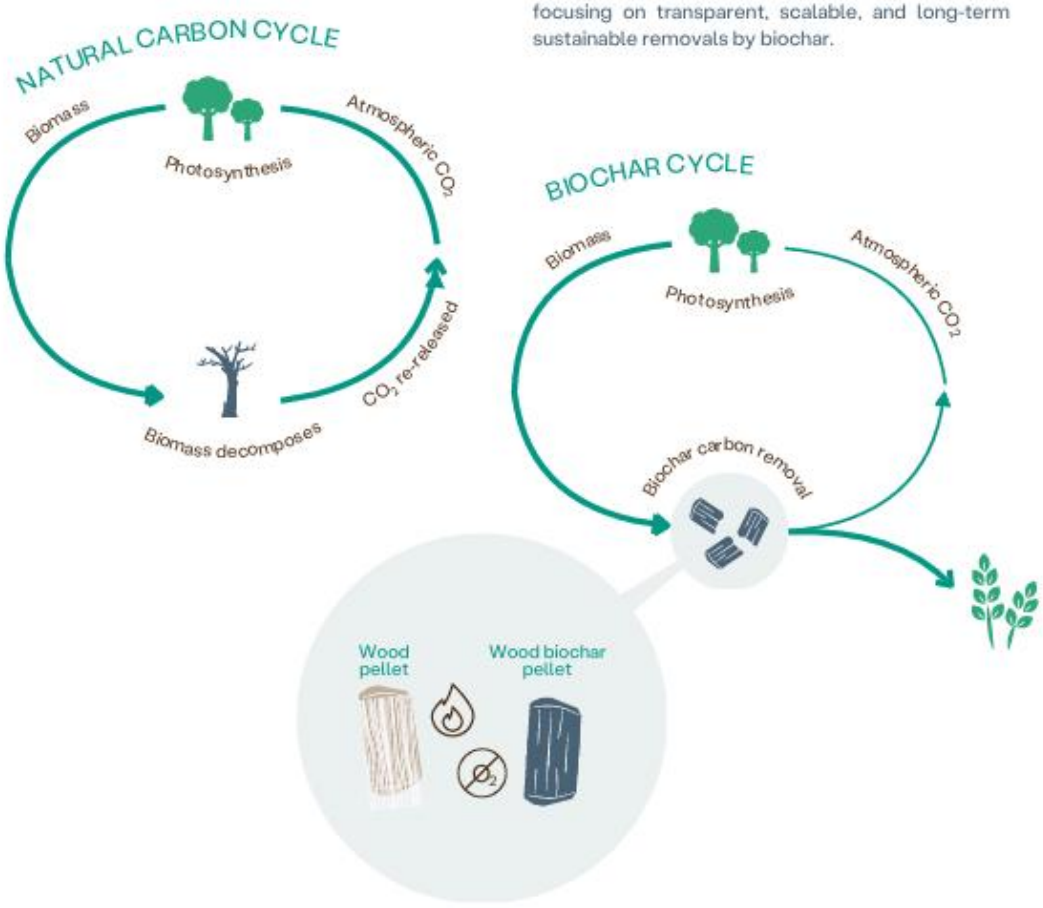
Risks must also be considered, such as unsustainable biomass sourcing, which could harm biodiversity (Smith et al., 2023). Besides, its production may emit particulates or greenhouse gases if not well controlled (Buss et al., 2022). Use of appropriate emissions management technologies is therefore critical.

Overall, biochar presents a low reversal risk compared to other CDR methods according to CRCF (2024), since once applied to soils, it is nearly impossible for it to be lost through fire or intentional removal (Chiaramonti et al., 2024).

C-SINK PROJECT

C-SINK is an EU-funded project that aims to establish the foundations for a standardized and transparent European Carbon Dioxide Removal (CDR) market.

For biochar, C-SINK is developing two distinct case studies at operational production and application sites: one in Oliveira de Azeméis, Portugal (Ibero Massa Florestal (IMF) and another linked to an industrial feedstock-to-product demonstration in the UK (Pyrogenesys (PYR)/Birmingham), where MRV is carried out in situ across the full production–application chain. Both case studies test MRV under real, open-system conditions, focusing on transparent, scalable, and long-term sustainable removals by biochar.



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11.3. Appendix L

AS - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

ARTIFICIAL SOILS (AF)

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, leaders of the European Union agreed on an ambitious goal: to make Europe climate-neutral by 2050. This means balancing the greenhouse gases we emit with actions that remove carbon dioxide from the atmosphere. This commitment builds on the promises made by EU countries when they signed the Paris Agreement in 2015, a global agreement to limit global warming to well below 2°C and ideally to 1.5°C above pre-industrial levels to reduce the worst impacts of climate change

.

To turn this vision into law, the EU introduced the European Climate Law in 2020 as part of the European Green Deal. This law legally commits the EU to climate neutrality by 2050 and sets a clear milestone for 2030: cutting net greenhouse gas emissions by at least 55% compared with 1990 levels. Looking ahead, the EU has also proposed an even more ambitious target, a 90% reduction by 2040 ((EU) 2021/1119, 2025).

Reaching these goals will require more than just reducing emissions. Although switching to renewable energy and improving energy efficiency are essential, they are not enough on their own. Some sectors—such as aviation, cement, and chemicals and steel industry—are very difficult to fully decarbonize. That is why carbon dioxide removal (CDR) is becoming increasingly important. It involves actively removing carbon dioxide from the air and storing it safely and durably, helping to balance remaining emissions and reduce the overall amount of CO_2 in the atmosphere.

Carbon removal is also needed because natural carbon sinks, like forests and soils, are becoming less effective due to climate change and land-use pressures. When combined with strong emissions reductions, CDR can help the EU reach net-zero. Beyond its climate benefits, CDR also presents opportunities for innovation, new industries, and job creation.

The EU is developing policies to support both nature-based solutions, such as tree planting and climate-friendly farming, and industrial technologies, including direct air capture and bioenergy with carbon capture and storage. To ensure trust and environmental integrity, the EU is setting up clear rules and certification systems for carbon removal, including the Carbon Removals and Carbon Farming (CRCF) Regulation (EU 2024/3012).

Economic incentives also play a key role. The EU Emissions Trading System (ETS), the EU's main tool for reducing emissions cost-effectively—can help create demand for verified carbon removals and encourage investment in these solutions.

Within this context, the C-SINK project, funded by Horizon Europe, aims to help build the foundations for a transparent and reliable European carbon removal market. The project focuses on developing trustworthy methods to measure, report, and verify carbon removal, ensuring that CDR contributes responsibly and effectively to Europe's climate goals while complementing existing EU and international efforts.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR is a general term for ways to take carbon dioxide (CO_2) out of the air and store it safely for a long time. The captured carbon can be stored underground in rock formations, in soils and plants, in the ocean, or in products that keep the carbon locked away for decades, centuries, or even longer.

CDR approaches fall into three main groups:



Nature-based solutions
These approaches use natural processes to absorb and store carbon.

- Planting trees (afforestation and

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reforestation) helps capture CO_2 as trees grow.
- Soil carbon storage improves farming and land-management practices so soils can hold more carbon.
- Peatland restoration involves rewetting damaged peatlands so they can store large amounts of carbon in the soil.

Engineered solutions

These rely on technology and industrial processes to remove carbon from the air.
- Direct Air Capture (DAC) uses machines and chemicals to pull CO_2 directly from the atmosphere.
- Carbon mineralisation locks CO_2 into solid rock so it cannot return to the air.

Hybrid solutions

These combine natural and technological approaches.
- Bioenergy with Carbon Capture and Storage (BECCS) uses plants to absorb CO_2 as they grow. When the plants are used to produce energy, the released CO_2 is captured and stored underground.
- Biochar is a charcoal-like material made from plant waste that stores carbon and can improve soil health when added to farmland.

Nature-based solutions are currently the most affordable and ready-to-use options, making them especially important in the near term. More advanced technological solutions are still developing but could play a bigger role later in the century. For this reason, the European Commission sees carbon removal as essential and is placing strong emphasis on nature-based approaches.

Other examples of carbon removal include:
- Enhanced rock weathering, where crushed rocks are spread on farmland to absorb CO_2 while also improving soil quality.
- Marine-based approaches, such as restoring coastal wetlands or adjusting ocean chemistry, which use natural ocean processes to capture and store carbon.

Some carbon removal methods, such as BECCS and Direct Air Carbon Capture and Storage (DACCS), use carbon capture and storage (CCS) technology to permanently store CO_2. These methods can lead to net negative emissions, meaning they reduce the overall amount of carbon dioxide in the atmosphere.

However, it is important to understand that CCS used on fossil fuel emissions only reduces emissions it does not remove carbon already in the atmosphere. For this reason, carbon capture and storage (CCS) and carbon dioxide removal (CDR) are related but not the same, and the terms should not be used interchangeably.

ARTIFICIAL SOILS

Soils play an important role in removing carbon dioxide (CO_2) from the air. Plants absorb CO_2 through photosynthesis, and some of that carbon ends up stored in soils. In addition, water moving through soil and underground systems can transform CO_2 into inorganic forms, such as dissolved carbon or solid minerals, which can remain stored for very long periods.

Soils are one of the largest carbon sinks on Earth. They hold about twice as much carbon as the atmosphere, making them a powerful but often overlooked part of the climate system. By contrast, when carbon is converted into inorganic forms, such as carbonate minerals, it can be locked away for much longer. This happens through natural processes like the formation of carbon-rich minerals in soils and through methods such as enhanced rock weathering, where crushed rocks help capture and store CO_2.

To strengthen carbon storage in soils, scientists are also developing artificial soils. These are specially designed soils created to both capture carbon and reuse waste materials. Artificial soils are made by carefully mixing organic and mineral wastes to create healthy, functioning soil. Depending on local needs and available materials, they can include items such as manure, food waste, plant trimmings, sawdust, ashes from biomass, sewage sludge, paper waste, or recycled construction materials.

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These materials are blended to achieve good soil quality, including the right balance of nutrients, structure, and acidity. Artificial soils can be used to restore damaged land, clean up polluted areas, and improve soil fertility. They can be added into existing soils to improve their functions e.g. water retention.

Because artificial soils contain a large share of human-made materials, they are classified as Technosols. This category includes many types of soils influenced by human activity, such as mine waste or construction fills and are designed for recycling waste materials (Figure 1).
Using engineered soils can help store carbon on land for long periods via soil-plant system offering a promising way to tackle CDR while reducing waste at the same time.

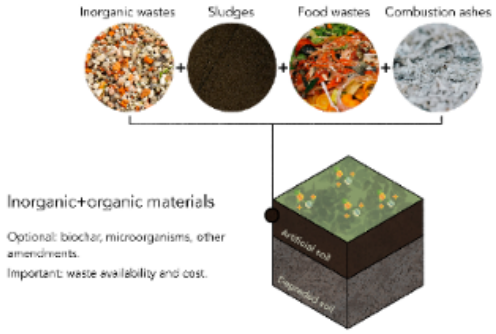


Figure 1. Diagram with examples of parent materials for artificial soil formulation

CURRENT STATE OF ARTIFICIAL SOILS AS CDR TECHNOLOGY

Artificial soils are made by carefully mixing natural and recycled materials- They are still mostly at the research and testing stage when it comes to removing carbon dioxide (CO_2) from the atmosphere. While they are already used to restore damaged land, green cities, and clean up polluted sites, scientists are still learning how to design and manage them specifically to store carbon for the long term and deliver reliable environmental benefits.

At this early stage, steady and long-term public support is very important. Artificial soils need years, and often decades, of testing to understand how much carbon they can store, how stable that carbon is, and how soil structure, microbes, and plants interact over time. Short-term funding can stop projects before useful results are achieved, slowing progress and innovation.

There is also uncertainty about how artificial soils will perform in different places. Results depend on local materials, climate, and how the soil is managed. Because of this uncertainty and the long time needed to see results, public institutions play a key role in sharing risks. Artificial soils still require upfront investment for site preparation, materials, monitoring, and long-term tracking, with benefits that may take years to appear.

Supportive policies are just as important as funding. Recognising artificial soils in climate research, land restoration plans, and soil-carbon programs helps create confidence and early demand. Clear policy signals can speed up learning and encourage innovation.

Artificial soils are now moving into a demonstration stage, where pilot projects are tested in real-world settings such as former mining areas, construction sites, roadsides, and urban spaces. These projects are larger than lab experiments but still risky, because long-term carbon storage and monitoring methods are not yet fully proven.

Demonstration projects help close the gap between research and wider use. They test how artificial soils perform at larger scales, how different waste materials can be safely reused, and how carbon storage can be measured in practice. Since these projects usually do not generate immediate income, they still rely heavily on public funding and support.

Public and political backing is especially important because artificial soils often use recycled materials like construction waste or mine residues, which can

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raise concerns about safety, regulation, and public acceptance. Strong institutional support can help overcome these barriers, simplify approvals, and encourage early users such as cities, landowners, and site managers.

At this stage, they would show carbon storage, trusted monitoring systems, and clear additional benefits such as healthier soils, better biodiversity, and less waste going to landfill.

To reach this stage, artificial soils need reliable sources of funding to cover construction, upkeep, and long-term monitoring. These could come from a mix of public and private sources, land restoration programs, infrastructure budgets, and incentives that reward recycling waste. As experience grows, costs are expected to fall, making artificial soils more competitive with other carbon-removal options.

Over time, artificial soils should become a normal part of land restoration, infrastructure development, and soil management reducing reliance on direct subsidies and becoming self-sustaining.

CONCLUSIONS FROM C-SINK PROJECT

A field pilot trial with artificial soils was carried out at Pasek mine within the framework of C-sink project. The purpose of this trial was to collect data to evaluate CDR with this technology by itself and also when is combined with EW and biochar. Six plots of 300 m2 were implemented at David's Mine from Pasek Minerales, in Landoi, Cariño, Spain (Figures 2 and 3).

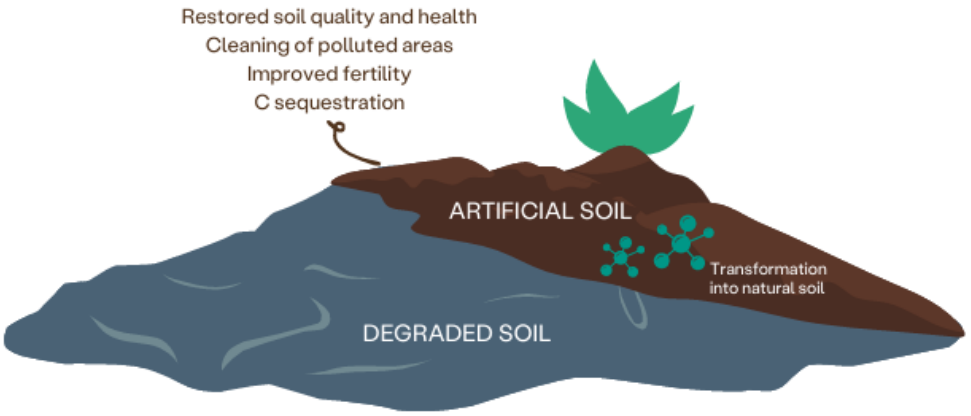


Figure 2. Aerial view of the pilot in February 2025 (4 artificial soil plots, 1 control where fertilizer was applied and trees and grasses were planted, and other second control plot that was unplanted).



Figure 3. Pictures that compare artificial soil plot (without amendments) with control plot (where fertilizer was applied) in February 2025.

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11.4. Appendix M

AF - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

AFFORESTATION (AF)

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, leaders of the European Union agreed on an ambitious goal: to make Europe climate-neutral by 2050. This means balancing the greenhouse gases we emit with actions that remove carbon dioxide from the atmosphere. This commitment builds on the promises made by EU countries when they signed the Paris Agreement in 2015, a global agreement to limit global warming to well below 2°C and ideally to 1.5°C above pre-industrial levels to reduce the worst impacts of climate change

.

To turn this vision into law, the EU introduced the European Climate Law in 2020 as part of the European Green Deal. This law legally commits the EU to climate neutrality by 2050 and sets a clear milestone for 2030: cutting net greenhouse gas emissions by at least 55% compared with 1990 levels. Looking ahead, the EU has also proposed an even more ambitious target, a 90% reduction by 2040 ((EU) 2021/1119, 2025).

Reaching these goals will require more than just reducing emissions. Although switching to renewable energy and improving energy efficiency are essential, they are not enough on their own. Some sectors—such as aviation, cement, and chemicals and steel industry—are very difficult to fully decarbonize. That is why carbon dioxide removal (CDR) is becoming increasingly important. It involves actively removing carbon dioxide from the air and storing it safely and durably, helping to balance remaining emissions and reduce the overall amount of CO_2 in the atmosphere.

Carbon removal is also needed because natural carbon sinks, like forests and soils, are becoming less effective due to climate change and land-use pressures. When combined with strong emissions reductions, CDR can help the EU reach net-zero. Beyond its climate benefits, CDR also presents opportunities for innovation, new industries, and job creation.

The EU is developing policies to support both nature-based solutions, such as tree planting and climate-friendly farming, and industrial technologies, including direct air capture and bioenergy with carbon capture and storage. To ensure trust and environmental integrity, the EU is setting up clear rules and certification systems for carbon removal, including the Carbon Removals and Carbon Farming (CRCF) Regulation (EU 2024/3012).

Economic incentives also play a key role. The EU Emissions Trading System (ETS), the EU's main tool for reducing emissions cost-effectively—can help create demand for verified carbon removals and encourage investment in these solutions.

Within this context, the C-SINK project, funded by Horizon Europe, aims to help build the foundations for a transparent and reliable European carbon removal market. The project focuses on developing trustworthy methods to measure, report, and verify carbon removal, ensuring that CDR contributes responsibly and effectively to Europe's climate goals while complementing existing EU and international efforts.

CARBON DIOXIDE REMOVAL (CDR) TECHNOLOGIES

CDR is a general term for ways to take CO_2 out of the air and store it safely long-term. The captured CO_2 can be stored underground in rock formations, in soils and plants, in the ocean, or in products that keep the carbon locked away for decades, centuries, or even on geological timescales (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

Land-based CDR approaches fall into two main groups:



Nature-based solutions
These approaches use natural processes to absorb and store carbon.

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- Planting trees (afforestation and reforestation) helps capture CO_2 by absorbing it from the air and storing it in biomass and soils.
- Improving farming and land-management practices so soils can hold more carbon
- Soil carbon sequestration: natural process where plants convert CO_2 from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration involves rewetting damaged peatlands so they can store large amounts of carbon in the soil.

Engineered solutions

These rely on technology and industrial processes to remove carbon from the air.

- Direct Air Carbon Capture and Storage (DACCS) uses turbines to pull CO_2 directly from the atmosphere and stores it underground in geological formations.
- Bioenergy with Carbon Capture and Storage (BECCS) uses plants to absorb CO_2 as they grow. When the plants are used to produce energy, the released CO_2 is captured and stored underground.
- Biochar is a charcoal-like material made by heating biomass and agricultural waste with little or no oxygen that stores carbon and can improve soil health when added to farmland.
- Enhanced rock weathering, where crushed alkaline rocks are spread on farmland to absorb CO_2 while also improving soil quality.

Nature-based solutions are currently the most affordable and ready-to-use options, making them especially important in the near term. More advanced technological solutions are still developing but could play an important role in near future. For this reason, the European Commission is placing strong emphasis on nature-based solutions (NbS). EC has preference for these NbS due to their higher level of development and their recognized environmental, social and economic co-benefits. Furthermore, they help to support the delivery of a range of ecosystem services. This focus is further reinforced by related EU policy frameworks, including the Green Infrastructure Strategy and the Biodiversity Strategy, with ecosystem restoration targets being especially significant. At the international level, similar principles were endorsed in March 2022, when the United Nations adopted a resolution on nature-based solutions at the fifth UN Environment Assembly (UNEA-5), closely aligning with the European Commission's definition.

Some carbon removal methods, such as BECCS and DACCS, use carbon capture and storage (CCS) technology to permanently store CO_2 (assuming well managed systems). Some studies indicated that these methods could lead to net negative emissions, meaning they reduce the overall amount of carbon dioxide in the atmosphere (Xie et al., 2025).

However, it is important to understand that CCS used on fossil fuel emissions only reduces emissions it does not remove carbon already in the atmosphere. For this reason, carbon capture and storage (CCS) and carbon dioxide removal (CDR) are related but not the same, and the terms should not be used interchangeably.

AFFORESTATION

Natural land ecosystems help remove CO_2 from the air mainly through photosynthesis. Plants take in CO_2 as they grow and store it in their leaves, wood, roots, and the soil. Forests are especially important because trees can store large amounts of carbon for long periods, both above ground in their trunks and branches and below ground in their roots and soils. Around the world, forests hold a major share of the carbon stored on land, making them a key part of how the planet regulates climate (figure 1).

Afforestation, or planting trees on land that has not been forested for a long time, removes carbon by allowing new forests to grow. Although forest soils can store carbon for many years, this storage is not permanent, fires, pests, storms, and natural decay can release carbon back into the atmosphere. For this reason, the long-term climate benefits of afforestation depend on how fast trees grow, which species are planted, where they are

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planted, and how the forests are managed. (Figure 2)

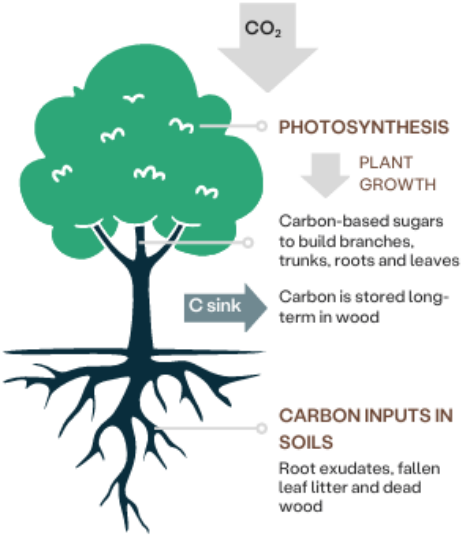


Figure 1. CO_2 fixation and carbon cycle in afforested ecosystems.



Figure 2. Steps procedure for afforestation.

Afforestation is often used on degraded, abandoned, or marginal land, where it can both remove carbon from the air and help restore ecosystems. The amount of carbon stored—and how long it stays stored—varies depending on local climate, soil conditions, tree species, and forest management practices. The long-term carbon storage also depends on the usage of wood: while it is possible to store a share of the carbon in timber products (e.g., buildings, furniture), some of the carbon from the leftover parts of the trees that remain in the woods (e.g., branches, stumps) will still be released to the atmosphere.

Designing successful afforestation projects requires thoughtful choices. Different tree species grow at different speeds, use water and nutrients differently, and vary in how well they cope with pests, diseases, and extreme weather. Planting a mix of native species is increasingly preferred because these forests are more resilient, support more wildlife, and are less vulnerable to large-scale damage than single-species plantations. Forest management practices, such as thinning or selective harvesting, also influence how much carbon remains stored in the forest over time.

Beyond climate benefits, afforestation can provide many additional advantages. It can help restore damaged land, protect soils from erosion, improve water regulation, support biodiversity, provide areas for education, learning and recreation as well as for physical and mental well-being, and contribute to local economies through sustainable timber production. When wood is used in long-lasting products, such as buildings or furniture, the carbon stored in the trees can remain locked away for many years, extending the climate benefits beyond the forest itself (Hasegawa et al. 2024).

Afforestation is considered a nature-based carbon removal solution. It works through natural biological processes, rather than industrial technologies, but its success still depends heavily on good planning, long-term management, and strong governance. Poorly designed projects such as planting the wrong species or relying on large monocultures can harm biodiversity, increase water stress, or make forests more vulnerable to fire and disease.

When carefully planned and combined with wider land-use and climate strategies, afforestation offers a practical and scalable way to remove

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carbon dioxide from the atmosphere. At the same time, it supports healthier ecosystems and more sustainable land management, making it a valuable tool in the response to climate change (Udawatta et al. 2022).



Figure 3. Plant preparation



Figure 4. Afforestation planting design

CURRENT STATE OF AFFORESTATION AS CDR TECHNOLOGY

Planting trees on previously non-forested land known as afforestation is a well-known practice, but it still needs ongoing research to work effectively to remove CO_2 from the atmosphere. Researchers are improving how trees are selected, where they are planted, how forests are managed, and how carbon stored in trees and soils is measured over time, especially as the climate changes (Li et al. 2025, Strauss et al. 2024).

Because forests take decades to grow, stable long-term funding and clear policies are essential. Even though tree planting is less expensive than high-tech carbon removal, it still carries risks such as drought, fire, pests, and uncertain growth. Public support helps manage these risks, especially for projects on degraded land or those testing new approaches like mixed-species forests.

Demonstration projects remain important to show that afforestation can store carbon reliably in real-world conditions. These projects also help improve how carbon storage is measured and build public trust by showing added benefits like healthier ecosystems, better water management, and rural jobs (Cook-Patton et al 2021).

Afforestation is now considered a mature and proven climate solution. The main challenge is scaling it up responsibly by securing enough land, funding, and long-term management. Over time, afforestation can become self-sustaining by fitting into normal land-use planning, forestry markets, and climate policies, reducing the need for ongoing public subsidies (Jovanelly et al. 2026).

CONCLUSIONS FROM C-SINK PROJECT

Afforestation has limits and risks. Large areas of land are needed, which can compete with farming or housing. Climate benefits take time to appear, and forests can lose stored carbon due to fires, pests, droughts, or poor management. Poorly planned projects such as large single-species plantations or planting trees in unsuitable places can harm biodiversity and water resources.

For these reasons, afforestation for maximising carbon capture works best as part of a wider climate strategy, not as a single solution. Combining it with other approaches such as improving soil carbon, using biochar, or pairing bioenergy with carbon capture can make carbon removal more reliable and reduce risks. This also helps use land more efficiently and supports wider goals related to energy, resource use, and the circular economy.

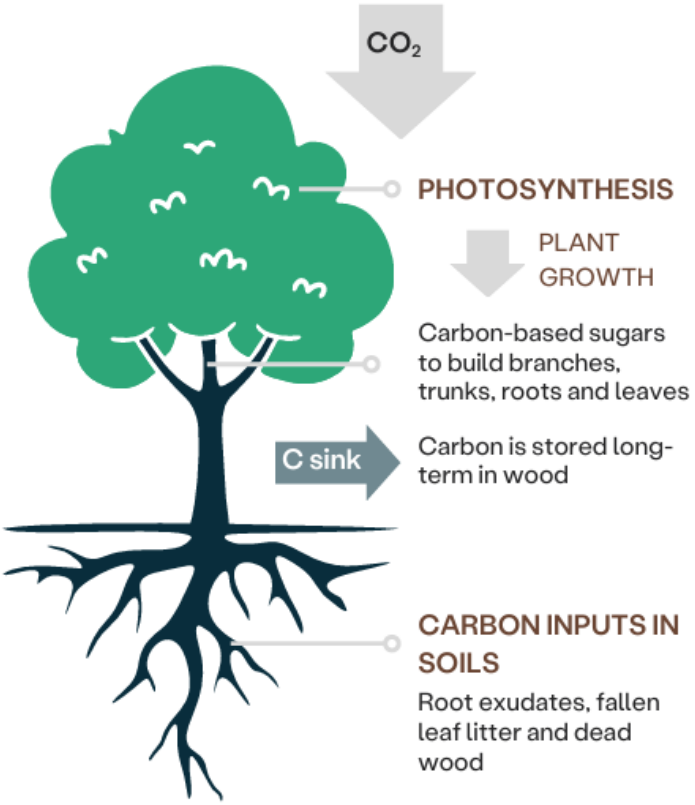
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To ensure trust and effectiveness, strong systems are needed to measure and track carbon storage in forests and soils over time. New tools, such as satellite monitoring, forest surveys, and digital data systems, help provide transparency and accountability at large scales.

Overall, when supported by long-term policies, good land-use planning, and sustainable forest management, afforestation can play an important role in tackling climate change. It is a practical, affordable, and multi-purpose solution that can remove carbon from the air while also restoring ecosystems and benefiting society.



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11.5. Appendix N

Synergies - L2

CARBON DIOXIDE REMOVAL TECHNOLOGIES (CDR-T):

SYNERGIES

CLIMATE-NEUTRAL SOCIETY BY 2050

In 2019, leaders of the European Union agreed on an ambitious goal: to make Europe climate-neutral by 2050. This means balancing the greenhouse gases we emit with actions that remove carbon dioxide from the atmosphere. This commitment builds on the promises made by EU countries when they signed the Paris Agreement in 2015, a global agreement to limit global warming to well below 2°C and ideally to 1.5°C above pre-industrial levels to reduce the worst impacts of climate change.

To turn this vision into law, the EU introduced the European Climate Law in 2020 as part of the European Green Deal. This law legally commits the EU to climate neutrality by 2050 and sets a clear milestone for 2030: cutting net greenhouse gas emissions by at least 55% compared with 1990 levels. Looking ahead, the EU has also proposed an even more ambitious target, a 90% reduction by 2040 ((EU) 2021/1119, 2025).

Reaching these goals will require more than just reducing emissions. Although switching to renewable energy and improving energy efficiency are essential, they are not enough on their own. Some sectors—such as aviation, cement, and chemicals and steel industry—are very difficult to fully decarbonize. That is why carbon dioxide removal (CDR) is becoming increasingly important. It involves actively removing carbon dioxide from the air and storing it safely and durably, helping to balance remaining emissions and reduce the overall amount of CO_2 in the atmosphere.

Carbon removal is also needed because natural carbon sinks, like forests and soils, are becoming less effective due to climate change and land-use pressures. When combined with strong emissions reductions, CDR can help the EU reach net-zero. Beyond its climate benefits, CDR also presents opportunities for innovation, new industries, and job creation.

The EU is developing policies to support both nature-based solutions, such as tree planting and climate-friendly farming, and industrial technologies, including direct air capture and bioenergy with carbon capture and storage. To ensure trust and environmental integrity, the EU is setting up clear rules and certification systems for carbon removal, including the Carbon Removals and Carbon Farming (CRCF) Regulation (EU 2024/3012).

Economic incentives also play a key role. The EU Emissions Trading System (ETS), the EU's main tool for reducing emissions cost-effectively—can help create demand for verified carbon removals and encourage investment in these solutions.

Within this context, the C-SINK project, funded by Horizon Europe, aims to help build the foundations for a transparent and reliable European carbon removal market. The project focuses on developing trustworthy methods to measure, report, and verify carbon removal, ensuring that CDR contributes responsibly and effectively to Europe's climate goals while complementing existing EU and international efforts.

CARBON DIOXIDE REMOVAL TECHNOLOGIES

CDR is a general term for ways to take CO_2 out of the air and store it safely long-term. The captured CO_2 can be stored underground in rock formations, in soils and plants, in the ocean, or in products that keep the carbon locked away for decades, centuries, or even on geological timescales (Brunner et al., 2024, Intergovernmental Panel on Climate Change [IPCC], 2018).

Land-based CDR approaches fall into two main groups:



Nature-based solutions
These approaches use natural processes to absorb and store carbon.

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- Planting trees (afforestation and reforestation) helps capture CO_2 by absorbing it from the air and storing it in biomass and soils.
- Improving farming and land-management practices so soils can hold more carbon
- Soil carbon sequestration: natural process where plants convert CO_2 from the air into organic matter through photosynthesis, that gets stored in the soil as stable organic carbon when litter is incorporated into soil.
- Peatland restoration involves rewetting damaged peatlands so they can store large amounts of carbon in the soil.

Engineered solutions

These rely on technology and industrial processes to remove carbon from the air.

- Direct Air Carbon Capture and Storage (DACCS) uses turbines to pull CO_2 directly from the atmosphere and stores it underground in geological formations.
- Bioenergy with Carbon Capture and Storage (BECCS) uses plants to absorb CO_2 as they grow. When the plants are used to produce energy, the released CO_2 is captured and stored underground.
- Biochar is a charcoal-like material made by heating biomass and agricultural waste with little or no oxygen that stores carbon and can improve soil health when added to farmland.
- Enhanced rock weathering, where crushed alkaline rocks are spread on farmland to absorb CO_2 while also improving soil quality.

Nature-based solutions are currently the most affordable and ready-to-use options, making them especially important in the near term. More advanced technological solutions are still developing but could play an important role in near future. For this reason, the European Commission is placing strong emphasis on nature-based solutions (NbS). EC has preference for these NbS due to their higher level of development and their recognized environmental, social and economic co-benefits. Furthermore, they help to support the delivery of a range of ecosystem services. This focus is further reinforced by related EU policy frameworks, including the Green Infrastructure Strategy and the Biodiversity Strategy, with ecosystem restoration targets being especially significant. At the international level, similar principles were endorsed in March 2022, when the United Nations adopted a resolution on nature-based solutions at the fifth UN Environment Assembly (UNEA-5), closely aligning with the European Commission's definition.

Some carbon removal methods, such as BECCS and DACCS, use carbon capture and storage (CCS) technology to permanently store CO_2 (assuming well managed systems). Some studies indicated that these methods could lead to net negative emissions, meaning they reduce the overall amount of carbon dioxide in the atmosphere (Xie et al., 2025).

However, it is important to understand that CCS used on fossil fuel emissions only reduces emissions it does not remove carbon already in the atmosphere. For this reason, carbon capture and storage (CCS) and carbon dioxide removal (CDR) are related but not the same, and the terms should not be used interchangeably.

SYNERGIES AMONG CDR TECHNOLOGIES

No single carbon removal method is perfect. Each option has limits related to cost, how much carbon it can store, how long the carbon stays stored, and possible environmental side effects. For this reason, experts increasingly agree that carbon removal should be tackled holistically as a system, using several approaches together rather than relying on just one. Nature already plays a major role in the carbon cycle. Plants and soils absorb large amounts of CO_2, and soils alone store more carbon than the atmosphere. Plants take in CO_2 as they grow, and some of that carbon ends up in soils through roots and microbial activity. Other natural processes can turn CO_2 into minerals, which have a potential to store CO_2 for much longer (1000s of years). However, these natural processes are slow and can be disrupted by climate, land use, or natural decay, which limits how much long-term carbon removal they can deliver on their own.

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Combining different carbon removal approaches can help overcome these limits. Therefore, recent research is increasingly focused on exploring how combining methods such as tree planting alongside biochar production, or artificial soils combined with enhanced rock weathering can remove more carbon than individual approaches alone and reduce the risk that it will be re-released into the atmosphere.

Artificial soils, which are being tested in C-SINK, are a good example of how this can work. Made from carefully selected organic and mineral waste materials, these soils can be designed to store carbon in multiple ways. Plants and microbes add organic carbon, while minerals help lock carbon into more permanent forms. Adding biochar provides stable carbon, which is harder for microbes to break down, and crushed minerals can help turn CO_2 into stable carbon compounds. Together, these processes improve both carbon storage and soil health.

These combined approaches can also link land use and energy systems. For example, trees or crops grown on restored land can be used to produce energy, while capturing and storing the released CO_2 underground or turning it into biochar. Other methods, such as enhanced rock weathering, speed up natural chemical reactions that absorb CO_2 and store it in water or rock. Overall, these approaches move carbon away from short-lived biological cycles and into longer-lasting storage.
Despite their promise, combined carbon removal systems are still at an early stage. Many methods are at different levels of development, and there is limited real-world data on how well they work together over time. Measuring and tracking carbon across these complex systems is also challenging, and clear, shared CDR standards are still being developed. Other challenges include competition for land, availability of materials, energy needs, and possible environmental trade-offs.

To move forward, CDR needs a step-by-step approach. This starts with pilot and demonstration projects that test combined solutions in real-world settings. These projects should be supported by long-term policies, reliable funding, and strong coordination across land, energy, and industry sectors. Better data, modelling tools, and digital technologies including artificial intelligence can help improve design, reduce risks, and guide future large-scale deployment (Cobo et al. 2023).

In summary, using CDR methods together offers a practical and resilient way to remove carbon from the atmosphere at the scale needed to meet climate goals. By combining natural processes, chemical stabilization and engineered storage, land-based solutions can deliver lasting climate benefits while also supporting healthier ecosystems, more efficient resource use, and sustainable land management.

CURRENT STATE OF THE SYNERGIES AMONG LEADING CDR TECHNOLOGIES

Using different CDR methods together rather than one at a time is still mostly at an early research and development stage. While approaches like tree planting, biochar, carbon capture from bioenergy, rock weathering, artificial soils, and microbial processes have each been studied on their own, there is much less experience with combining them in real projects. Research shows that information on these combined approaches is limited and scattered, so more structured studies are needed to understand how they work together and what benefits they can deliver.

At this early stage, long-term and reliable funding and policy support are especially important. Studying how different CDR methods interact takes time and involves many fields, including land use, energy systems, materials, and soil and climate science. Some benefits of combining methods such as increased carbon storage in soils or more efficient use of biomass and agricultural wastes only become clear after many years. Short-term or uncertain funding can limit this work before solid conclusions are reached.

There is also a high level of uncertainty when methods are combined. Mixing technologies can increase risks related to additionality and permanence. Because of this, public institutions

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need to help manage early risks and support coordination. Just as importantly, policies need to recognise and support combined approaches, not just individual technologies, to encourage collaboration across different sectors.

These combined approaches move into a demonstration stage when tested in real-world pilot projects. Examples include adding biochar to newly planted forests, using crushed rocks in combination with artificial soils, or linking tree planting with BECCS. At this stage, projects begin to scale up, but they still involve risks because the full benefits have not yet been proven outside controlled settings (Adun et al., 2024).

Demonstration projects are essential because they show how combined systems perform in practice. They help measure how much carbon is removed, identify environmental benefits or drawbacks, and test practical challenges. They are also crucial for improving methods to measure and track carbon, since most current approaches are designed for individual technologies rather than combined systems.

Strong political and public support is especially important at this early stage. Projects that combine several CDR methods often fall under multiple rules covering land use, energy, waste, and industry, which can make approvals complex. Continuous research, targeted incentives, and engagement with communities and stakeholders help build confidence, reduce barriers, and encourage early adoption. Demonstration projects also help identify which combinations work best in different places.

In the mature stage, combining CDR methods will likely become standard practice rather than an experiment. Instead of selecting one solution at a time, climate strategies will likely deploy well-tested combinations that remove more carbon, use resources more efficiently, and reduce environmental risks. These combined, synergistic systems will be repeatable and ready for large-scale implementation.

To reach this stage, stable and reliable funding sources are needed. Because combined systems rely on multiple components working together, such as trees providing material for bioenergy or biochar-funding needs to be aligned across technologies. Funding may come from carbon markets, energy production, land restoration funding, and incentives for recycling materials. As experience grows and systems improve, cost is expected to fall, making combined approaches more affordable than single solutions.

Even at maturity, long-term stability remains essential. Policy and governance across CDR-related sectors must be predictable and consistent should consider not only cost but also wider impacts such as biodiversity, land use, and public acceptance. Over time, government support can shift away from direct funding toward clear rules, reliable carbon accounting, and coordination across policies.

In the long run, combining CDR methods can become a standard part of land management, energy production, and industrial practices. With the right policies in place, these integrated carbon removal systems can play a major role in helping Europe reach its climate goals in a reliable and sustainable way.

CONCLUSIONS FROM C-SINK PROJECT

Research from the C-SINK project shows that it is likely that using CDR methods individually might not be an efficient strategy for EU climate targets and energy transition. Better results may come from combining different approaches such as tree planting, biochar, artificial soils, BECCS, and enhanced rock weathering. Working together, these methods are likely to remove more carbon than if deployed in isolation, store it more securely, and provide added benefits for ecosystems and resource use.

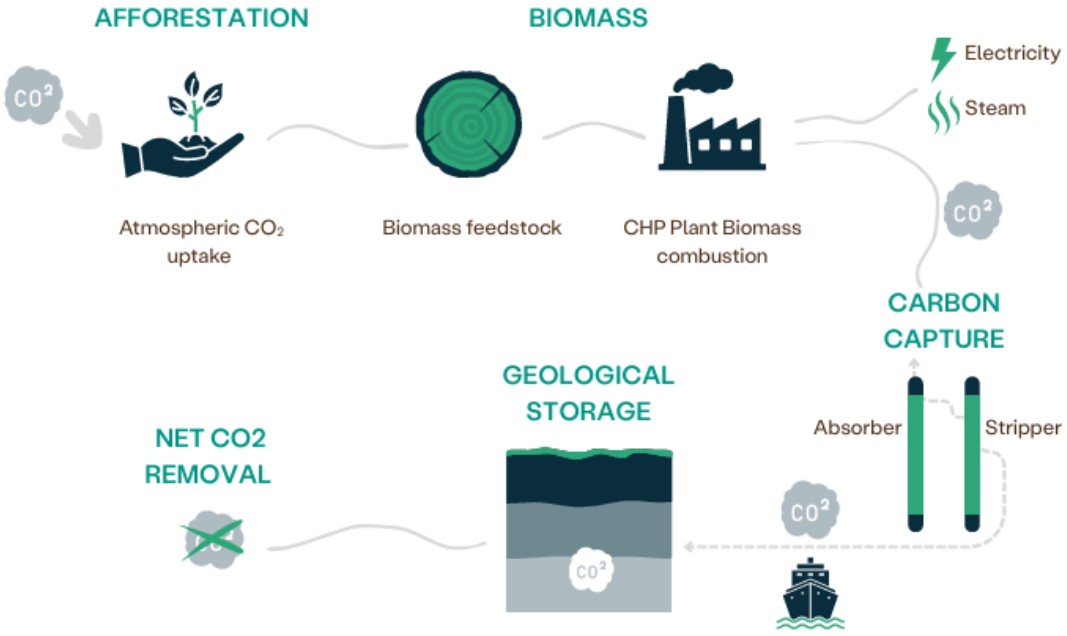
However, scaling up these combined approaches is challenging. Different methods are at different stages of development, which creates uncertainty about performance and long-term carbon storage. Large-scale projects can also put pressure on land, water, and biodiversity if not carefully designed.

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High costs, energy needs, transport requirements, and limited systems for measuring and tracking carbon across multiple CDR methods add further barriers.

To move forward, C-SINK highlights the need for step-by-step progress, starting with pilot projects that test combined solutions in real-world settings. Clear, long-term policies and financial incentives are essential to reduce risk and attract investment. Better data, monitoring tools, and digital technologies can also help improve performance and build trust.

Over time, the goal is to make integrated carbon removal a normal part of land management, energy systems, and industry, turning early experiments into a reliable pillar of Europe's climate strategy.



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