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

C-SINK– FACTSHEET 7 DELIVERED BY ISMC, UED, MEM, CSIC, ICAMCYL

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 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 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.

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 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.

REFERENCES

- Adun, H., Ampah, J. D., Bamisile, O., & Hu, Y. (2024). The synergistic role of carbon dioxide removal and emission reductions in achieving the Paris Agreement goal. *Sustainable Production and Consumption, 45*, 386–407. https://doi.org/10.1016/j.spc.2024.01.004
- Brunner, C., Hausfather, Z., & Knutti, R. (2024). Durability of carbon dioxide removal is critical for Paris climate goals. *Communications Earth & Environment, 5*, 645. https://doi.org/10.1038/s43247-024-01808-7
- Cobo, S., Negri, V., Valente, A., Reiner, D., Hamelin, L., Dowell, N., & Guillén-Gosálbez, G. (2023). Sustainable scale-up of negative emissions technologies and practices: Where to focus. *Environmental Research Letters, 18*. https://doi.org/10.1088/1748-9326/acacb3
- European Commission. (2019). *The European Green Deal (COM(2019) 640 final)*. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640
- European Parliament, & Council of the European Union. (2021). *Regulation (EU) 2021/1119 … (European Climate Law)*. https://data.europa.eu/eli/reg/2021/1119/oj
- Intergovernmental Panel on Climate Change. (2018). Annex I: Glossary (J. B. R. Matthews, Ed.). In *Global warming of 1.5°C* (pp. 541–562). Cambridge University Press. https://doi.org/10.1017/9781009157940.008
- Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., & Vaughan, N. E. (Eds.). (2024). *The State of Carbon Dioxide Removal 2024* (2nd ed.). https://doi.org/10.17605/OSF.IO/F85QJ
- United Nations Framework Convention on Climate Change. (2016). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement

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