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

C-SINK– FACTSHEET 5 DELIVERED BY ISMC, FCO, CES, ICAMCYL

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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