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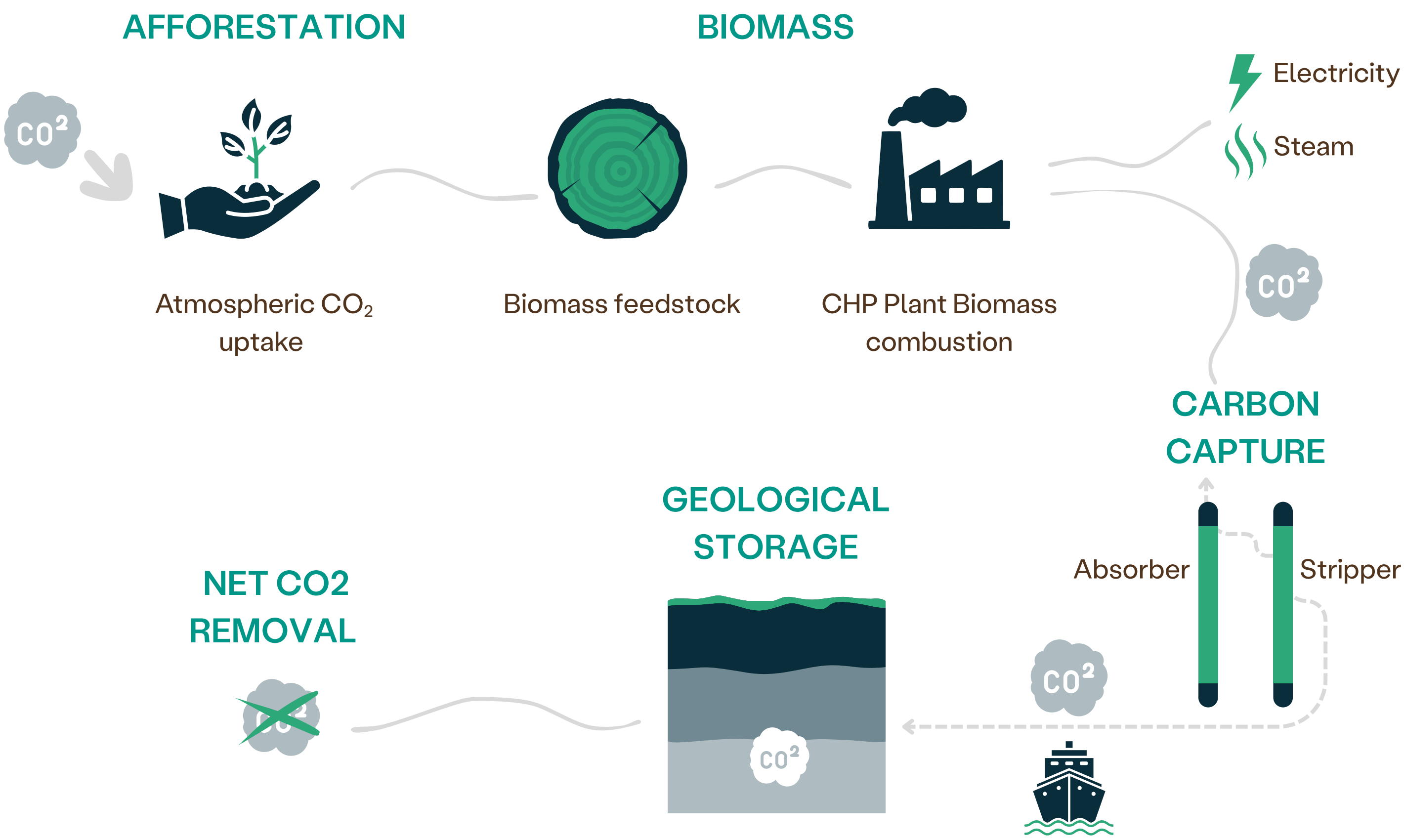
High costs, energy needs, transport requirements, and limited systems for measuring and tracking carbon across multiple CDR methods add further barriers.

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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